State of the Ocean Report for the Beaufort Sea Large Ocean Management Area

A. Niemi[1], J. Johnson[1], A. Majewski[1], H. Melling[2], J. Reist[1], W. Williams[2]

[1]Freshwater Institute
Fisheries and Oceans Canada
501 University Crescent
Winnipeg, MB
R3T 2N6

[2]Institute of Ocean Sciences
Fisheries and Oceans Canada
9860 West Saanich Road
Sidney BC
V8L 4B2

2012

Canadian Manuscript Report of Fisheries and Aquatic Sciences 2977

Fisheries and Oceans | Pêches et Océans

Canada

Canadian Manuscript Report of Fisheries and Aquatic Sciences

Manuscript reports contain scientific and technical information that contributes to existing knowledge but which deals with national or regional problems. Distribution is restricted to institutions or individuals located in particular regions of Canada. However, no restriction is placed on subject matter, and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Manuscript reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base Aquatic Sciences and Fisheries Abstracts.

Manuscript reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-900 in this series were issued as Manuscript Reports (Biological Series) of the Biological Board of Canada, and subsequent to 1937 when the name of the Board was changed by Act of Parliament, as Manuscript Reports (Biological Series) of the Fisheries Research Board of Canada. Numbers 1426 - 1550 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Manuscript Reports. The current series name was changed with report number 1551.

Rapport manuscrit canadien des sciences halieutiques et aquatiques

Les rapports manuscrits contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui traitent de problèmes nationaux ou régionaux. La distribution en est limitée aux organismes et aux personnes de régions particulières du Canada. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports manuscrits peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports manuscrits sont résumés dans la base de données Résumés des sciences aquatiques et halieutiques.

Les rapports manuscrits sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 900 de cette série ont été publiés à titre de Manuscrits (série biologique) de l'Office de biologie du Canada, et après le changement de la désignation de cet organisme par décret du Parlement, en 1937, ont été classés comme Manuscrits (série biologique) de l'Office des recherches sur les pêcheries du Canada. Les numéros 901 à 1425 ont été publiés à titre de Rapports manuscrits de l'Office des recherches sur les pêcheries du Canada. Les numéros 1426 à 1550 sont parus à titre de Rapports manuscrits du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 1551.

Canadian Manuscript Report of
Fisheries and Aquatic Sciences 2977

2012

State of the Ocean Report for the Beaufort Sea Large Ocean Management Area

A. Niemi[1], J. Johnson[1], A. Majewski[1], H. Melling[2], J. Reist[1], W. Williams[2]

[1]Freshwater Institute
Fisheries and Oceans Canada
501 University Crescent
Winnipeg, MB
R3T 2N6

[2]Institute of Ocean Sciences
Fisheries and Oceans Canada
9860 West Saanich Road
Sidney BC
V8L 4B2

Canadian Manuscript Report of Fisheries and Aquatic Sciences

Manuscript reports contain scientific and technical information that contributes to existing knowledge but which deals with national or regional problems. Distribution is restricted to institutions or individuals located in particular regions of Canada. However, no restriction is placed on subject matter, and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Manuscript reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base Aquatic Sciences and Fisheries Abstracts.

Manuscript reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-900 in this series were issued as Manuscript Reports (Biological Series) of the Biological Board of Canada, and subsequent to 1937 when the name of the Board was changed by Act of Parliament, as Manuscript Reports (Biological Series) of the Fisheries Research Board of Canada. Numbers 1426 - 1550 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Manuscript Reports. The current series name was changed with report number 1551.

Rapport manuscrit canadien des sciences halieutiques et aquatiques

Les rapports manuscrits contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui traitent de problèmes nationaux ou régionaux. La distribution en est limitée aux organismes et aux personnes de régions particulières du Canada. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports manuscrits peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports manuscrits sont résumés dans la base de données Résumés des sciences aquatiques et halieutiques.

Les rapports manuscrits sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 900 de cette série ont été publiés à titre de Manuscrits (série biologique) de l'Office de biologie du Canada, et après le changement de la désignation de cet organisme par décret du Parlement, en 1937, ont été classés comme Manuscrits (série biologique) de l'Office des recherches sur les pêcheries du Canada. Les numéros 901 à 1425 ont été publiés à titre de Rapports manuscrits de l'Office des recherches sur les pêcheries du Canada. Les numéros 1426 à 1550 sont parus à titre de Rapports manuscrits du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 1551.

Canadian Manuscript Report of
Fisheries and Aquatic Sciences 2977

2012

State of the Ocean Report for the Beaufort Sea Large Ocean Management Area

A. Niemi[1], J. Johnson[1], A. Majewski[1], H. Melling[2], J. Reist[1], W. Williams[2]

[1]Freshwater Institute
Fisheries and Oceans Canada
501 University Crescent
Winnipeg, MB
R3T 2N6

[2]Institute of Ocean Sciences
Fisheries and Oceans Canada
9860 West Saanich Road
Sidney BC
V8L 4B2

© Her Majesty the Queen in Right of Canada, 2012.
Cat. No. Fs 97-4/2977E ISSN 0706-6473

Correct citation for this publication:

Niemi, A., Johnson, J., Majewski, A., Melling, H., Reist, J. and Williams, W. 2012. State of the Ocean Report for the Beaufort Sea Large Ocean Management Area. Can. Manuscr. Rep. Fish. Aquat. Sci. 2977: vi + 51 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Niemi, A., Johnson, J., Majewski, A., Melling, H., Reist, J. and Williams, W. 2012. State of the Ocean Report for the Beaufort Sea Large Ocean Management Area. Can. Manuscr. Rep. Fish. Aquat. Sci. 2977: vi + 51 p.

The Beaufort Sea Large Ocean Management Area (LOMA) is the only Arctic area designated for Integrated Management (IM) under the legislative framework of Canada's *Oceans Act*. The Beaufort Sea LOMA covers an extensive area (1 107 694 km^2) of northwestern Canada and encompasses the marine portion of the Inuvialuit Settlement Region (ISR). Six communities with strong connections to the land and ocean are directly considered in the IM planning of the Beaufort Sea LOMA including; Aklavik, Inuvik, Ulukhaktok, Paulatuk, Sachs Harbour and Tuktoyaktuk. Through the process of IM the first Marine Protected Area (MPA), Tarium Niryutait, was created within the LOMA in August 2010. The LOMA is characterized by estuarine, shelf and basin waters as well as seasonal and multi-year sea ice. The Mackenzie River, polynyas and flaw lead play a key role in productivity and diversity within the LOMA. This report builds on existing ecosystem assessments for the Beaufort Sea and the LOMA, providing new information on select ecosystem components for the period 2005-2010.

RÉSUMÉ

Niemi, A., Johnson, J., Majewski, A., Melling, H., Reist, J. and Williams, W. 2012. State of the Ocean Report for the Beaufort Sea Large Ocean Management Area. Can. Manuscr. Rep. Fish. Aquat. Sci. 2977: vi + 51 p.

La zone étendue de gestion des océans (ZEGO) de la mer de Beaufort est la seule zone arctique soumise à la gestion intégrée (GI) en vertu du cadre législatif de la *Loi sur les océans* du Canada. La ZEGO de la mer de Beaufort s'étend sur une large superficie (1 107 694 km^2) au nord-ouest du Canada et comprend la zone maritime de la région désignée des Inuvialuits (RDI). Six communautés ayant des liens importants avec la terre et l'océan sont directement prises en considération dans la planification de la gestion intégrée de la ZEGO de la mer de Beaufort : Aklavik, Inuvik, Ulukhaktok, Paulatuk, Sachs Harbour et Tuktoyaktuk. Grâce au processus de gestion intégrée, la première zone de protection marine (ZPM), Tarium Niryutait, a été créée dans la ZEGO en août 2010. La ZEGO est caractérisée par des eaux d'estuaire, de bassin et de plateau, ainsi que par des glaces de mer saisonnières ou pluriannuelles. Le fleuve Mackenzie, les polynies et les chenaux de séparation jouent un rôle clé dans la productivité et la diversité de la ZEGO. Ce rapport se fonde sur des évaluations existantes de l'écosystème de la mer de Beaufort et de la ZEGO et fournit de nouveaux renseignements sur des éléments particuliers de l'écosystème pour la période de 2005 à 2010.

LOMA OVERVIEW

The Beaufort Sea Large Ocean Management Area (LOMA) is one of five priority areas identified for Integrated Ocean Management under Canada's *Ocean Act* (1997). Fisheries and Oceans Canada (DFO) is responsible for leading and implementing Integrated Management (IM). Under IM, a precautionary approach is taken to ensure sustainable use, development and protection of areas and resources and the incorporation of social, cultural and economic values are included in the development and implementation of ocean management. An ecosystem approach to management is upheld ensuring the sustainability of healthy marine environments while providing due consideration to other ocean users.

The Beaufort Sea LOMA (Fig. 1) covers approximately 1 107 694 km^2 and encompasses the marine portion of the Inuvialuit Settlement Region (ISR). The western boundary of the LOMA is defined by the ISR boundary. The LOMA covers some 750 km of coastal area. Associated with the LOMA are the communities of Paulatuk, Tuktoyaktuk, Sachs Harbour, Aklavik, Inuvik and Ulukhaktok (Holman) (Fig. 1). The LOMA includes diverse ecosystems such as the Mackenzie Delta estuary, Beaufort Shelf, Cape Bathurst Polynya, submarine canyons and deep basin features such as the Beaufort Gyre.

The initial assessment of the Beaufort Sea LOMA resulted in a comprehensive Ecosystem Overview and Assessment Report (EOAR) that included the identification of Ecologically and Biologically Significant Areas (EBSAs) and Ecologically Significant Species and Communities (ESSCs) for the LOMA (Cobb et al. 2008). In 2009 the Integrated Ocean Management Plan (IOMP) for the Beaufort Sea LOMA was released. These outcomes represent the efforts a number of individuals representing Aboriginal, Territorial and Federal government departments, management bodies, industry and northern coastal community members with interest in the Beaufort Sea.

This report provides new information primarily from the period 2005-2010 for the Beaufort Sea LOMA. This new data and information is referenced from recent publications, while some is still unpublished. The goal of this report is to provide current information on select ecosystem components rather than an extensive ecosystem overview. The 2005-2010 data highlight some recent ecosystem trends that, on their own, are limited in their capacity to address questions of anthropogenic or climate-driven change relative to the extensive natural variability of ecosystem components in the LOMA. This report builds upon existing ecosystem overviews and management documents that provide thorough background information for the LOMA area (Table 1). Many of the ecosystem components presented here focused on the on the coastal and shelf area of the LOMA (Fig. 1). However, new oceanographic information for the offshore, including the Beaufort Gyre, is presented in sections 1-3.

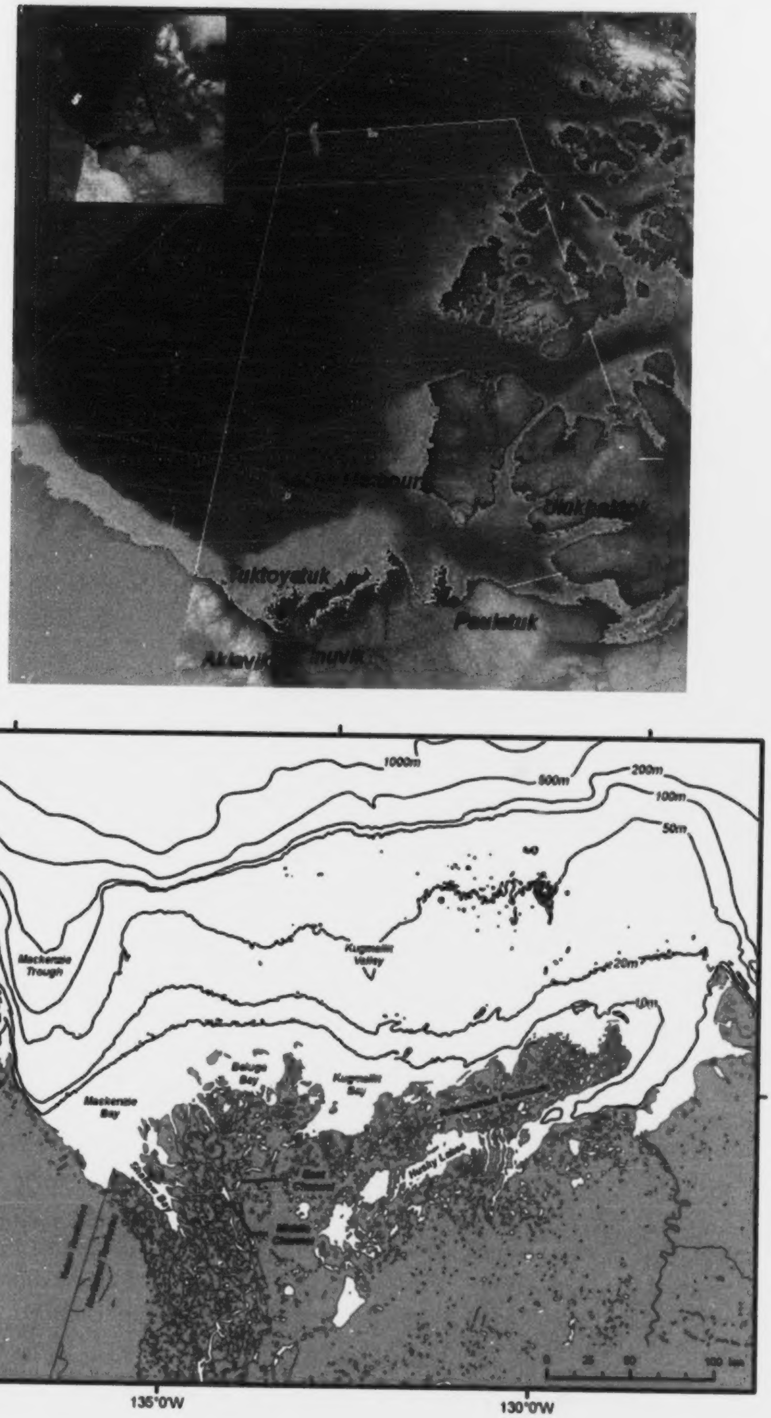


Figure 1. Boundaries of the Beaufort Sea LOMA and the six ISR communities located within (top). The western coastal and shelf (≤ 200 m) portion of the LOMA is shown in detail (bottom).

Table 1. Summary of recent ecosystem, socio-economic assessments and management documents for the Beaufort Sea LOMA area.

Title	Year	Reference
An ecological and Oceanographic Assessment of the Beaufort Sea Region: Evaluation of the Risks Associated with Ballast Water Exchange.	In prep	DFO Can. Sci. Advis. Sec. Res. Doc. (in preparation)
Ecosystem Overview Report for the Darnley Bay Area of Interest (AOI)	In press	DFO Can. Sci. Advis. Sec. Res. Doc. 2011/062. vi + 63 p.
2010 NWT Environmental Audit Status of the Environment Report	2011	http://www.aadnc-aandc.gc.ca/eng/1317759452812
Information in support of indicator selection for monitoring the Tarium Niryutait Marine Protected Area (TNMPA)	2010	DFO Can. Sci. Advis. Sec. Res, Doc. 2010/094. vi + 47 p.
Ecosystem status and trends report: Arctic Marine Ecozones	2010	DFO Can. Sci. Advis. Sec. Res. Doc. 2010/066. viii + 66 p.
The Yukon North Slope Pilot Project: An Environmental Risk Characterization using a Pathways of Effects Model	2009	Can. Manuscr. Rep. Fish. Aquat. Sci. 2896: vi + 57p.
Mapping Traditional Knowledge Related to the Identification of Ecologically and Biologically Significant Areas in the Beaufort Sea	2009	Can. Manuscript Rep. Fish. Aquat. Sci. 2895: iii + 25p.
Beaufort Sea Partnership Integrated Ocean Management Plan (IOMP) for the Beaufort Sea: 2009 and Beyond	2009	http://www.beaufortseapartnership.ca
The Beaufort Sea Integrated Ocean Management Planning Atlas	2009	http://www.beaufortseapartnership.ca
Beaufort Sea Social, Cultural and Economic Overview and Assessment Report (SCEOAR)	2008	http://www.beaufortseapartnership.ca
Beaufort Sea Large Ocean Management Area: Ecosystem Overview and Assessment Report	2008	Can. Tech. Rep. Fish. Aquat. Sci. 2780: ii-ix + 188 p.

ECOSYSTEM STRESSORS

Similar to other ice-dominated seas present in the Arctic, the Canadian Beaufort Sea has recently been affected, to varying degrees, by a range of stressors. These stressors are expected to continue in the near future, possibly increase in intensity, and their effects may interact or cumulate to result in uncertain outcomes. Stressors that can induce current and future changes within the Beaufort Sea LOMA include climate change, contaminants, oil and gas development, shipping, and aquatic invasive species. Fisheries of marine resources, often a key stressor in marine regions, are also described although currently not considered a key stressor. A brief overview of these stressors and activities is presented here, providing the context for potential impacts on the ecosystem components discussed in this report.

Climate Change and Variability

Natural variability in the climate system and anthropogenic forcings impacting the rates and patterns of change cause both direct and indirect effects on the Beaufort Sea

ecosystem. Direct effects may include declines in seasonal duration, spatial coverage (i.e., northwards retreat of median summer margins), and average age (thickness) of sea ice. Earlier melt/break-up and later freeze-up of seasonal sea ice can alter the physical, chemical and biotic pathways supporting coastal populations of exploitable biota. Subsiding coastlines, in combination with increasing storm frequencies and reductions in coastal ice, are enhancing coastal erosion (Mason and Solomon 2007). Consequently, indirect ecosystem effects of climate change such as the degradation of coastal permafrost and mobilization of high sediment loads into nearshore environments may be positive (e.g., nutrient supply) or negative (e.g., shallowing of migratory fishes habitat).

Climate change effects at a regional scale in the LOMA may be related to changes in the fresh water balance of the LOMA. This may be due to increased amounts and longer periods of fresh water input from the Mackenzie River (Prouse et al. 2009) and/or changes in flow through the Bering Strait and/or ice melt effects (Proshutinsky et al. 2009). Synergisms among these physical forcings may exacerbate ecosystem effects which likely include enhanced straying of migratory sub-arctic biota (and thus potential colonisation) into the LOMA and changes in productivity and trophic pathways. Effects from climate change will continue into the foreseeable future and effects on ecosystems may become more acute as feedbacks and synergies continue.

Contaminants

Organic and inorganic contaminants are delivered to the LOMA via atmospheric and marine/freshwater pathways. In addition, migratory biota have the potential to transport contaminants or disease into the LOMA. The presence of contaminants and their pathways are impacted by changes that affect physical and biological interactions in Arctic ecosystems. Both the absolute volume of delivery and the re-processing (including liberation from local stores and bioaccumulation) of contaminants to the ecosystem appear to be exacerbated as a result of climate change (Macdonald et al. 2005).

Oil and Gas Development

The Beaufort Sea LOMA has a long history of exploratory activities, primarily seismic work, for oil and gas reserves, and several exploratory wells have been drilled in the nearshore area in past decades. Proven reserves of natural gas occur in the immediate vicinity of the Mackenzie Delta both on land and in shallow water areas. Reserves of oil are suspected to occur at greater depths along the slope and drop-off from the Mackenzie Shelf. Accordingly, developments of both types of hydrocarbons are likely in the near future, with a deepwater exploratory well possible within the next few years.

Shipping

Routine community re-supply by barge represents the longest and most regular shipping in the LOMA. The Canadian Coast Guard routinely has two vessels which traverse the area as part of their Arctic operations. Seismic vessels also enter the area and historically this has been episodic in occurrence, but this activity may be increasing in recent years. Mitigation procedures have been implemented to reduce the impact of seismic noise on marine mammals. Effects of noise on fishes may be relevant but is a topic for which limited information is currently available. Given the relevance of this area to larger scale

issues of climate change, the presence of research vessels in the area has increased over the past few years. These include coastal research vessels as well as larger icebreakers working more offshore. Shipping potentially represents a stressor (e.g., noise disturbance, ice-breaking disruption of habitats, potential for spills or release of contaminants) of increasing importance particularly if oil and gas development occurs in the near future.

Aquatic Colonizing and Invasive Species
Climate change may increase the potential for colonization (i.e., successful entry, reproduction and establishment of populations) of biota which typically are not present in the LOMA. Routes for colonization include surface waters that may transport Pacific fauna (e.g., non-natal species of Pacific Salmon) and mid-layer marine waters transporting Atlantic fauna. Of less concern to marine environments is colonization via northward migrations in freshwater corridors such as the Mackenzie River. An additional concern is the potential for direct introduction of invasive species via ship transits into the area through fouled hulls and/or ballast water (DFO 2010). Currently, no zones within the LOMA are recommended as a potential Alternative Ballast Water Exchange Zone (ABWEZ) for commercial vessels.

Fisheries of Marine Resources
Marine biota consisting of anadromous coastal fishes (i.e., Dolly Varden Char (*Salvelinus malma*)), Arctic Char (*Salvelinus alpinus*), Broad Whitefish (*Coregonus nasus*), Lake/Humpback Whitefish (*Coregonus clupeaformis*), Arctic Cisco (*Coregonus autumnalis*), Least Cisco (*Coregonus sardinella*) and Inconnu (*Stenodus leucichthys*), marine mammals (i.e., Beluga (*Delphinapterus leucas*), Ringed Seal (*Phoca hispida*), Bearded Seal (*Erignathus barbatus*), Polar Bear (*Ursus maritimus*), and occasionally Bowhead (*Balaena mysticetus*)) and to a very limited degree marine fishes (e.g., Pacific Herring (*Clupea pallasii*), Saffron Cod (*Eleginus gracilis*)) are harvested by coastal Inuvialuit in the LOMA. These fisheries occur in the coastal areas or for anadromous fishes in freshwater locations immediately inland during autumn upstream migrations. Anadromous fishes which migrate to overwintering and spawning locations further inland are also harvested by Indigenous Peoples including Gwich'in, Sahtu and Dene. High productivities of anadromous fishes in this area are determined by accessibility, productivity and quality of the nearshore zone of mixed fresh and marine waters. All present fisheries are classified as subsistence, that is, domestic food fisheries. Moreover, all fisheries have been and continue to be sustainable. Past attempts at commercial fisheries for migratory anadromous fishes have proven unviable due to a combination of high costs (particularly transport to southern markets) and highly variable fish population abundances. Increases in populations of Indigenous Peoples are occurring and may result in increased subsistence fishing in the near future. However, recent harvests have tended to be below those of a few decades ago. Very limited recreational fisheries occur in the area, primarily targeting the same anadromous or freshwater species harvested by the local Indigenous Peoples.

1. PHYSICAL OCEANOGRAPHY, 2005-2010

Atmosphere

Conditions for life in the Beaufort Sea are determined by ice cover, surface temperature and salinity and the upwelling of dissolved nutrients from depth. All of these driving factors vary greatly between winter and summer and all are strongly influenced by wind. Patterns of surface wind are most clearly and concisely represented by the distribution of atmospheric pressure. Figures 2 and 3 display average atmospheric pressure at the sea surface for the north polar region in winter (October through April) and summer (May through September) periods, respectively. The Beaufort Sea is in the lower right quadrant of each map. The summer/winter split corresponds roughly to the seasons for freeze and thaw. The latter is of greatest interest for marine productivity.

The upper left map of Figures 2 and 3 displays, for reference, a 30-year average (1981-2010). Other maps display conditions during each of the five focus years of this report (2005-2006 to 2009-2010 for winter, 2006-2010 for summer). In winter, the bottom half of each map (Fig. 2) is dominated by high air pressure (red shades). The winters of 2006-2007 and 2008-2009 are fairly similar to the long-term average, but those for other years differ greatly. The extension of the Siberian High across the Beaufort Sea was weak during 2005-2006 and very strong during 2009-2010. In 2007-2008 there was an unusually strong and isolated high over the Beaufort Sea. Winds blow approximately parallel to the lines of constant pressure, clockwise around high pressure – the closer the lines, the stronger the wind. Therefore, the winds blowing from the east across the southern Beaufort were unusually strong during the winters of 2007-2008 and 2009-2010 and relatively weak in 2005-2006 and 2008-2009.

High pressure over the Beaufort Sea is on average lower in summer than in winter. The summertime pattern of pressure during 2006 is fairly similar to the long-term average, but there was unusually high pressure over the Beaufort in all four subsequent summers, particularly in 2007 and 2010. The force of the east wind on the sea surface was correspondingly strong (close spacing of isobars, Fig. 3). These unusual patterns of wind have contributed to faster ice drift, thinner ice in winter, greater expanse of open water in summer and strongly enhanced upwelling of nutrient rich water onto the continental shelf.

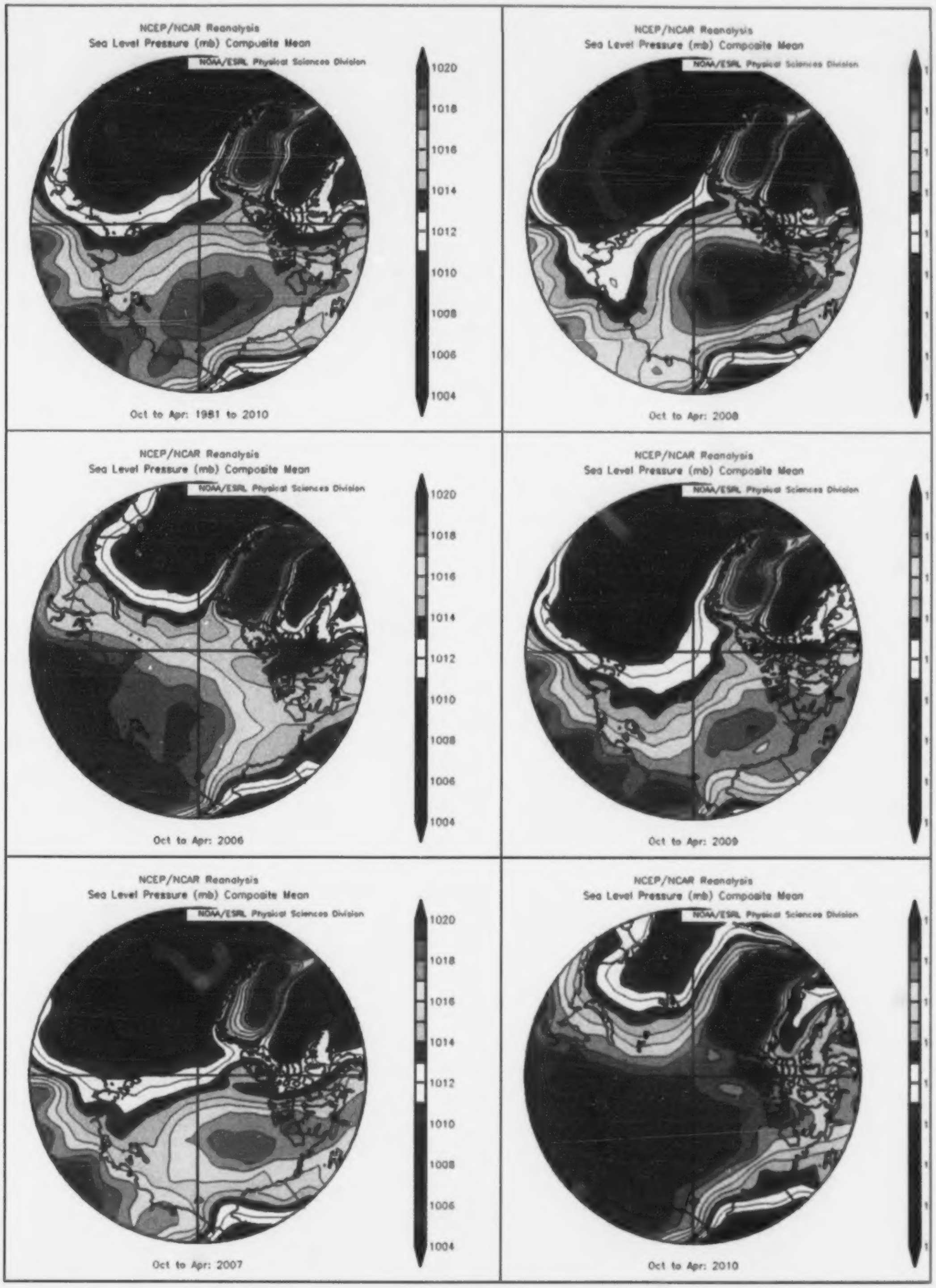


Figure 2. Average sea-level atmospheric pressure in winter (Oct-Apr) for the 30-year period 1981-2010 (upper left), and for each winter 2006-2010. Data from the NCEP re-analysis project (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl).

1. PHYSICAL OCEANOGRAPHY, 2005-2010

Atmosphere

Conditions for life in the Beaufort Sea are determined by ice cover, surface temperature and salinity and the upwelling of dissolved nutrients from depth. All of these driving factors vary greatly between winter and summer and all are strongly influenced by wind. Patterns of surface wind are most clearly and concisely represented by the distribution of atmospheric pressure. Figures 2 and 3 display average atmospheric pressure at the sea surface for the north polar region in winter (October through April) and summer (May through September) periods, respectively. The Beaufort Sea is in the lower right quadrant of each map. The summer/winter split corresponds roughly to the seasons for freeze and thaw. The latter is of greatest interest for marine productivity.

The upper left map of Figures 2 and 3 displays, for reference, a 30-year average (1981-2010). Other maps display conditions during each of the five focus years of this report (2005-2006 to 2009-2010 for winter, 2006-2010 for summer). In winter, the bottom half of each map (Fig. 2) is dominated by high air pressure (red shades). The winters of 2006-2007 and 2008-2009 are fairly similar to the long-term average, but those for other years differ greatly. The extension of the Siberian High across the Beaufort Sea was weak during 2005-2006 and very strong during 2009-2010. In 2007-2008 there was an unusually strong and isolated high over the Beaufort Sea. Winds blow approximately parallel to the lines of constant pressure, clockwise around high pressure – the closer the lines, the stronger the wind. Therefore, the winds blowing from the east across the southern Beaufort were unusually strong during the winters of 2007-2008 and 2009-2010 and relatively weak in 2005-2006 and 2008-2009.

High pressure over the Beaufort Sea is on average lower in summer than in winter. The summertime pattern of pressure during 2006 is fairly similar to the long-term average, but there was unusually high pressure over the Beaufort in all four subsequent summers, particularly in 2007 and 2010. The force of the east wind on the sea surface was correspondingly strong (close spacing of isobars, Fig. 3). These unusual patterns of wind have contributed to faster ice drift, thinner ice in winter, greater expanse of open water in summer and strongly enhanced upwelling of nutrient rich water onto the continental shelf.

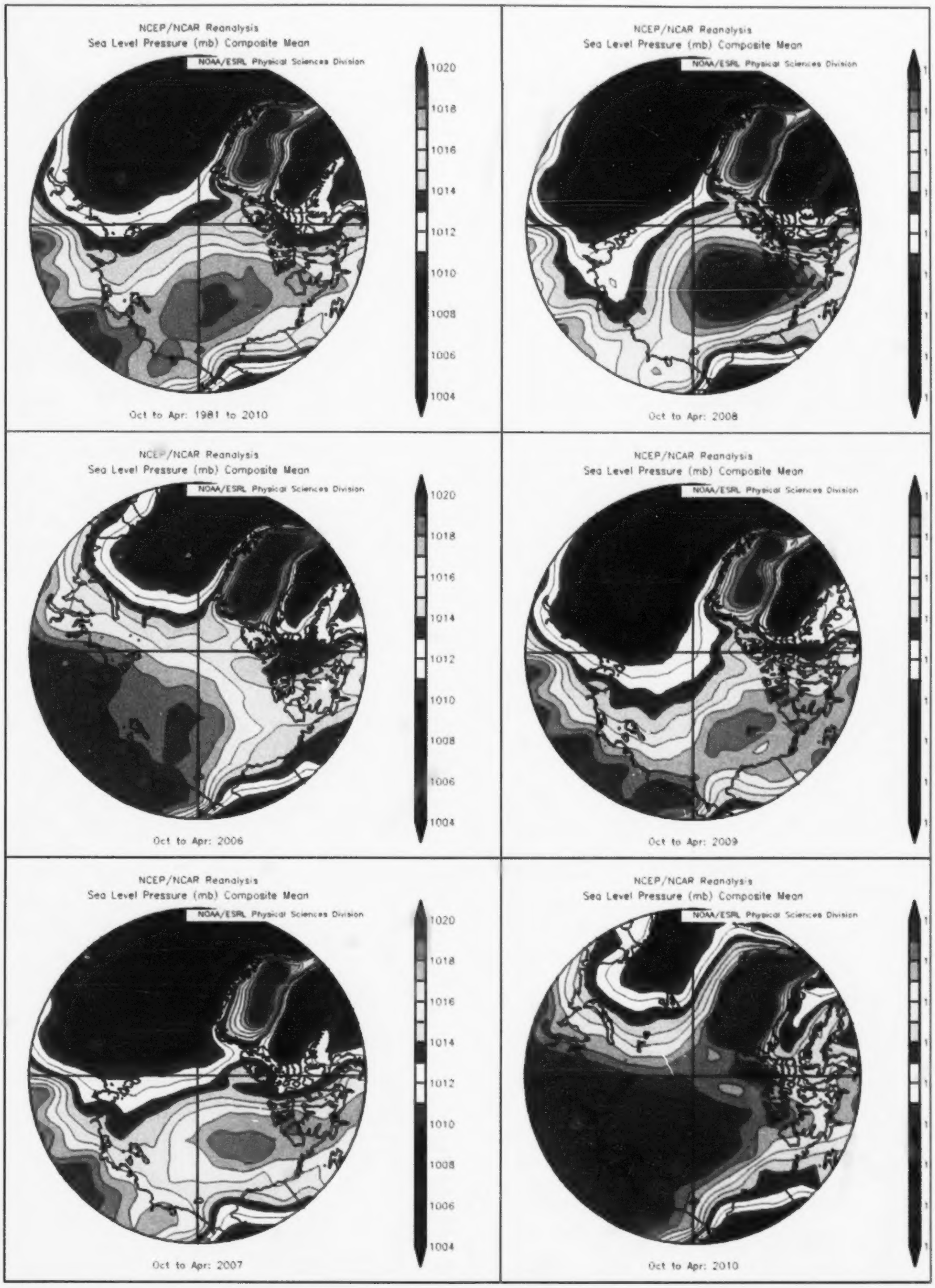


Figure 2. Average sea-level atmospheric pressure in winter (Oct-Apr) for the 30-year period 1981-2010 (upper left), and for each winter 2006-2010. Data from the NCEP re-analysis project (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl).

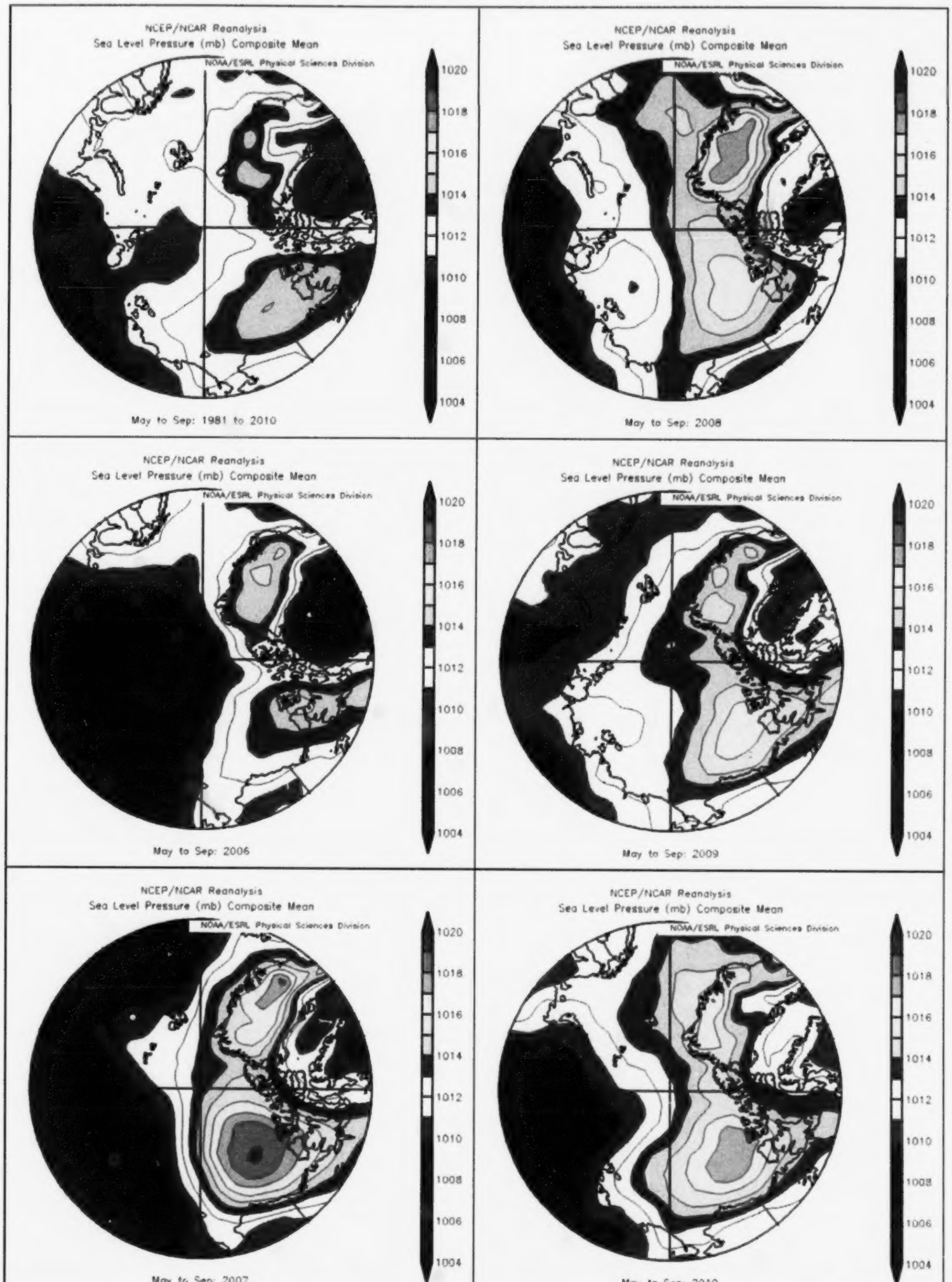


Figure 3. Average sea-level atmospheric pressure in summer (May-Sep) for the 30-year period, 1981-2010 (upper left), and for each summer 2006-2010. Data from the NCEP re-analysis project (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl).

Mackenzie Estuary

The Mackenzie River is a huge freshwater source for the continental shelf. The low density and high opacity of the discharge may inhibit marine primary production by restricting access by algae to nutrients and light. Average annual discharge of the Mackenzie measured at Arctic Red River was 317 km^3 between 2006 and 2010. Inter-annual variations were small (±6%), with a high of 334 km^3 in 2009 and a low of 291 km^3 in 2010 (Fig. 4). The onset of freshet was earliest in 2010 and two weeks later in 2008.

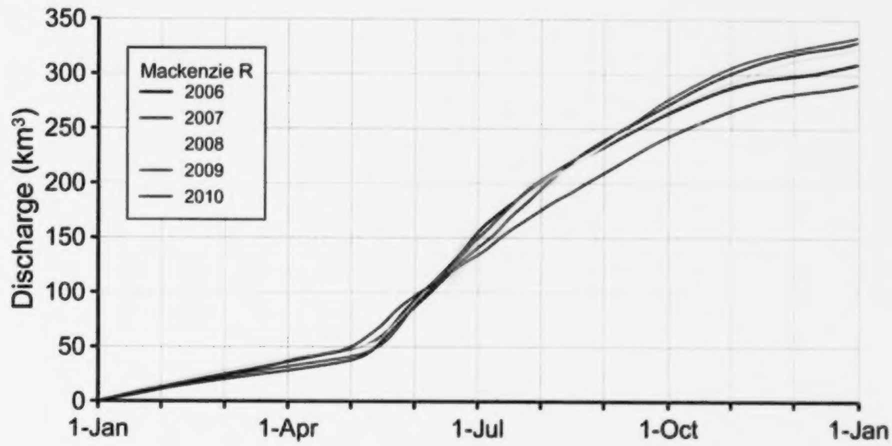


Figure 4. Annual average discharge of the Mackenzie River measured at Arctic Red River, 2006-2010. Data from the Water Survey of Canada: www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm.

Sea-ice Cover

Fast Ice

Rupture dates of the fast-ice barriers in Shallow and Kugmallit Bays (Fig. 5) were estimated from the Canadian Weekly Ice Chart (http://www.ec.gc.ca/glaces-ice/). Plotted dates may be late because the charting schedule is weekly.

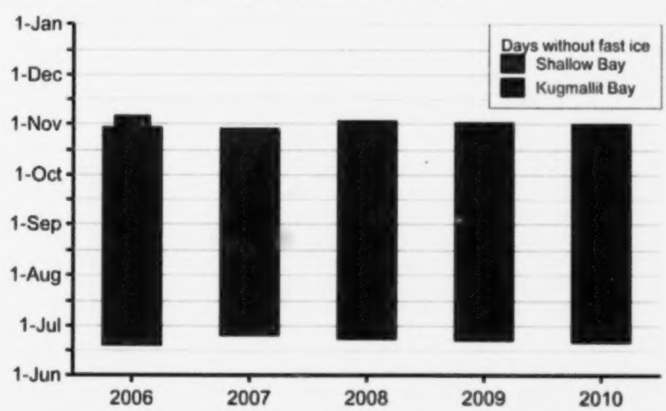


Figure 5. Dates without fast ice in Shallow and Kugmallit Bays, coastal Beaufort Sea LOMA.

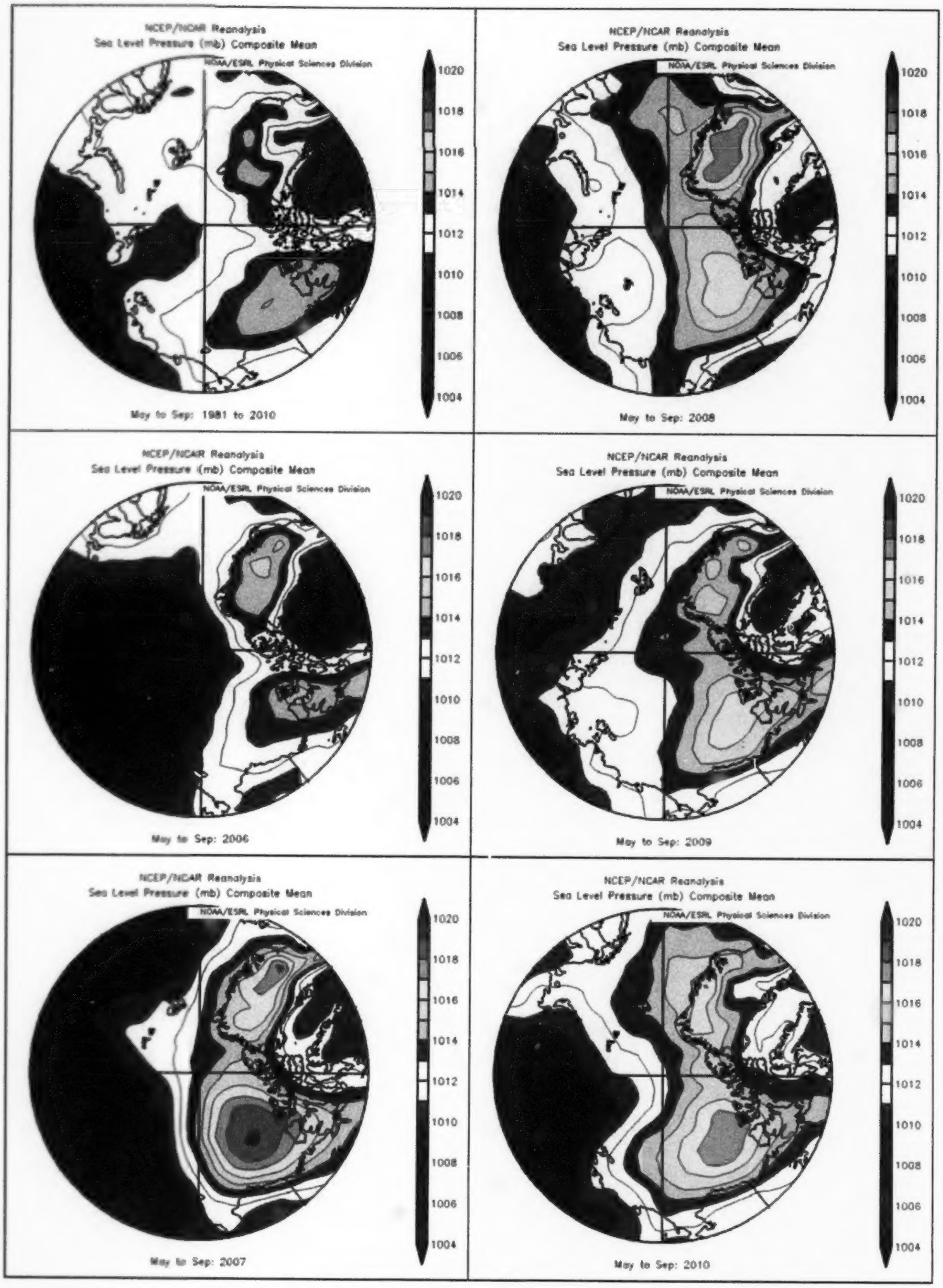


Figure 3. Average sea-level atmospheric pressure in summer (May-Sep) for the 30-year period, 1981-2010 (upper left), and for each summer 2006-2010. Data from the NCEP re-analysis project (http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl).

Mackenzie Estuary

The Mackenzie River is a huge freshwater source for the continental shelf. The low density and high opacity of the discharge may inhibit marine primary production by restricting access by algae to nutrients and light. Average annual discharge of the Mackenzie measured at Arctic Red River was 317 km^3 between 2006 and 2010. Inter-annual variations were small (±6%), with a high of 334 km^3 in 2009 and a low of 291 km^3 in 2010 (Fig. 4). The onset of freshet was earliest in 2010 and two weeks later in 2008.

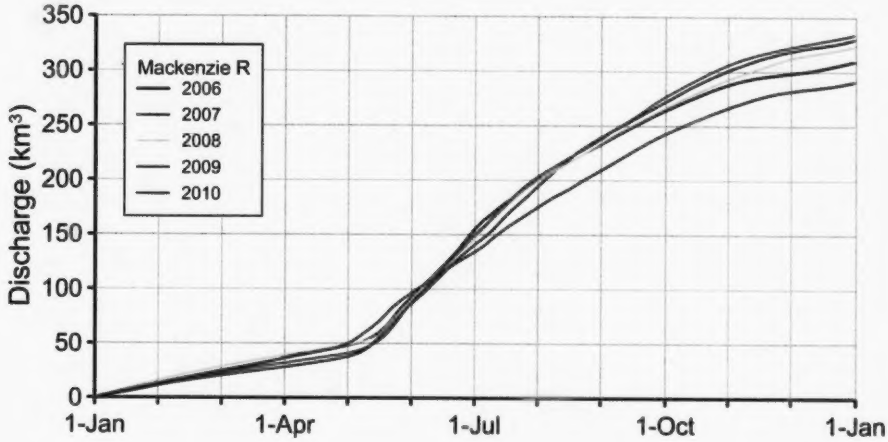


Figure 4. Annual average discharge of the Mackenzie River measured at Arctic Red River, 2006-2010. Data from the Water Survey of Canada: www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm.

Sea-ice Cover

Fast Ice

Rupture dates of the fast-ice barriers in Shallow and Kugmallit Bays (Fig. 5) were estimated from the Canadian Weekly Ice Chart (http://www.ec.gc.ca/glaces-ice/). Plotted dates may be late because the charting schedule is weekly.

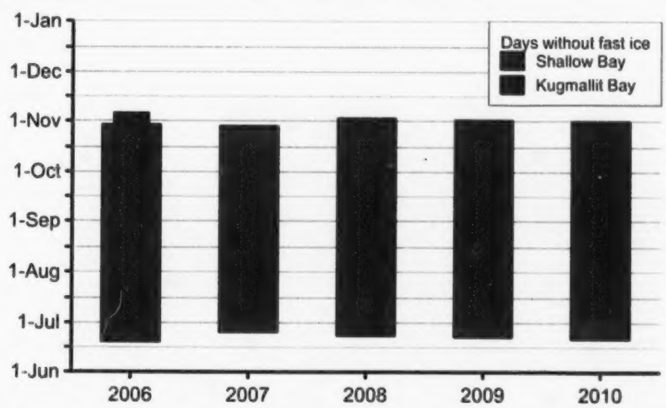


Figure 5. Dates without fast ice in Shallow and Kugmallit Bays, coastal Beaufort Sea LOMA.

The rupture date has varied little over the last five years. Fast ice blocks Beluga access to the Mackenzie estuary in early summer. The rupture of the ice barrier across Kugmallit Bay typically occurred about a week later than that of the barrier across Shallow Bay. The variation in the dates of re-established fast ice was also small.

Canada Basin

Summer ice cover is an important environmental control on the Beaufort Sea marine ecosystem. Ice conditions with the LOMA vary greatly within and among years based on weekly ice charts compiled by the Canadian Ice Service. In this section, conditions have been summarized for three areas of the transitional ice zone of greatest ecological interest (Mackenzie Shelf, Amundsen east, Amundsen west), and for a reference area of generally heavy ice in the Canada Basin (Fig. 6).

The left hand panels in Figure 6 display, via the shaded background, the long-term median of ice concentration through the summer. Typically ice has always been present at high concentration in the Canada Basin, and the minimum concentration in mid September has been high, about 8 tenths. Conditions in 2006 and 2009 replicated the long-term median quite well, although open pack ice persisted beyond mid October in 2006. Summer ice was particularly sparse in 2008 and for a particularly long period. Conditions in 2007 and 2010 were intermediate, but still more benign than the long-term median. In none of the last five summers did ice cover appreciably exceed the long-term median. The right hand panels in Figure 6 display the anomalies in total accumulated coverage (TAC) for the last 30 years, for total ice cover and just multi-year ice. TAC for this study is the area-time average of concentration between 15 May and 15 October. The right hand panels reveal declines in ice cover, with particularly low multi-year ice presence during the last three summers. However, the TAC trends are not statistically significant at the 95% level (shaded band around the regression line). This means that the most likely explanation for these trends, based on analysis of probability, is natural variation.

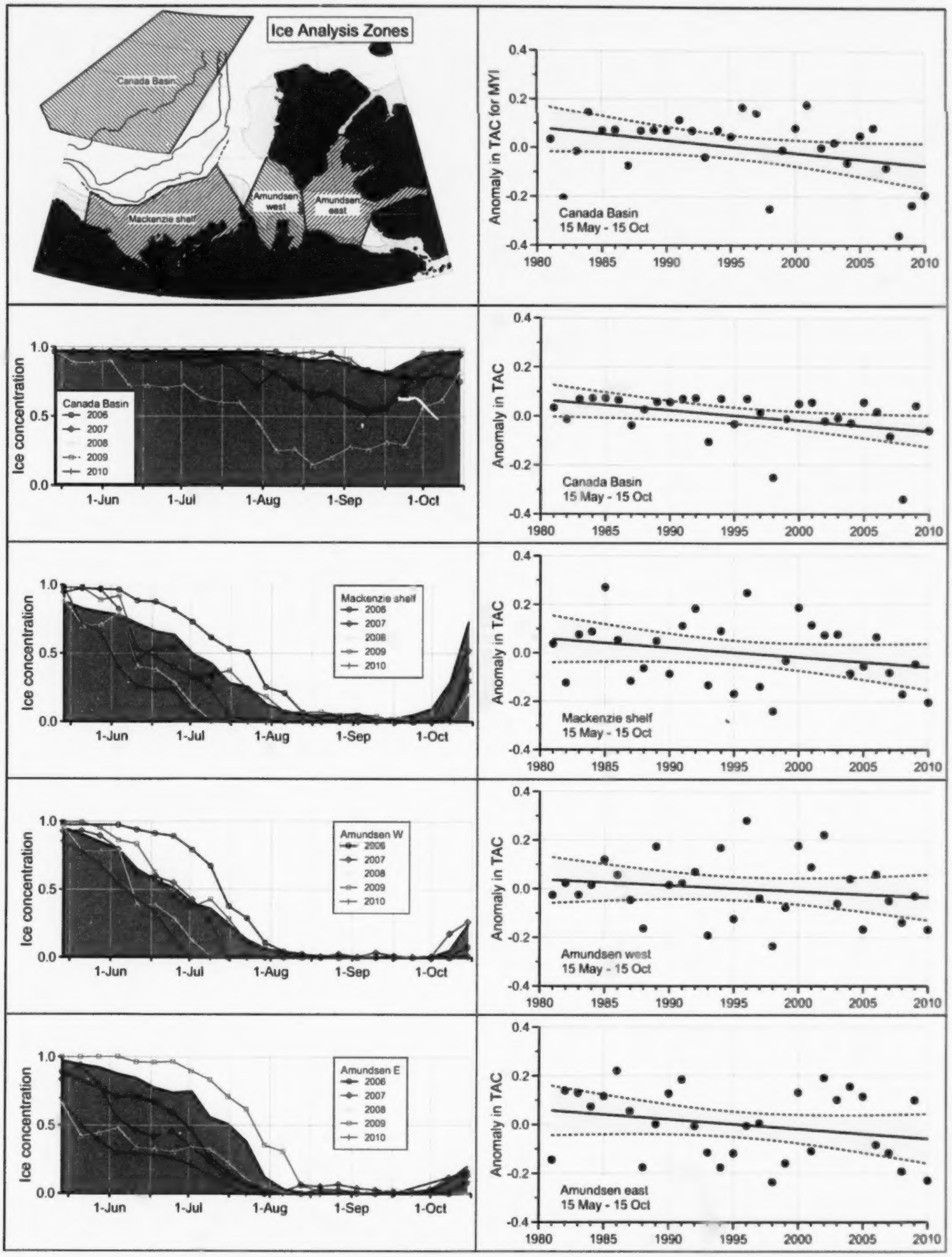


Figure 6. Summer ice concentrations (left-hand panels) and 30 year total accumulated coverage (TAC) sea-ice anomalies for the Canada Basin, Mackenzie Shelf and east and west Amundsen Gulf (right-hand panels). Graphs were prepared using the on-line statistical ice-analysis tool available at the CIS web site, http://dynaweb.cis.ec.gc.ca/IceGraph20/?lang=en.

The results shown in Figure 6 for the three shelf regions (Mackenzie Shelf, Amundsen west, Amundsen east) can be summarized as follows:

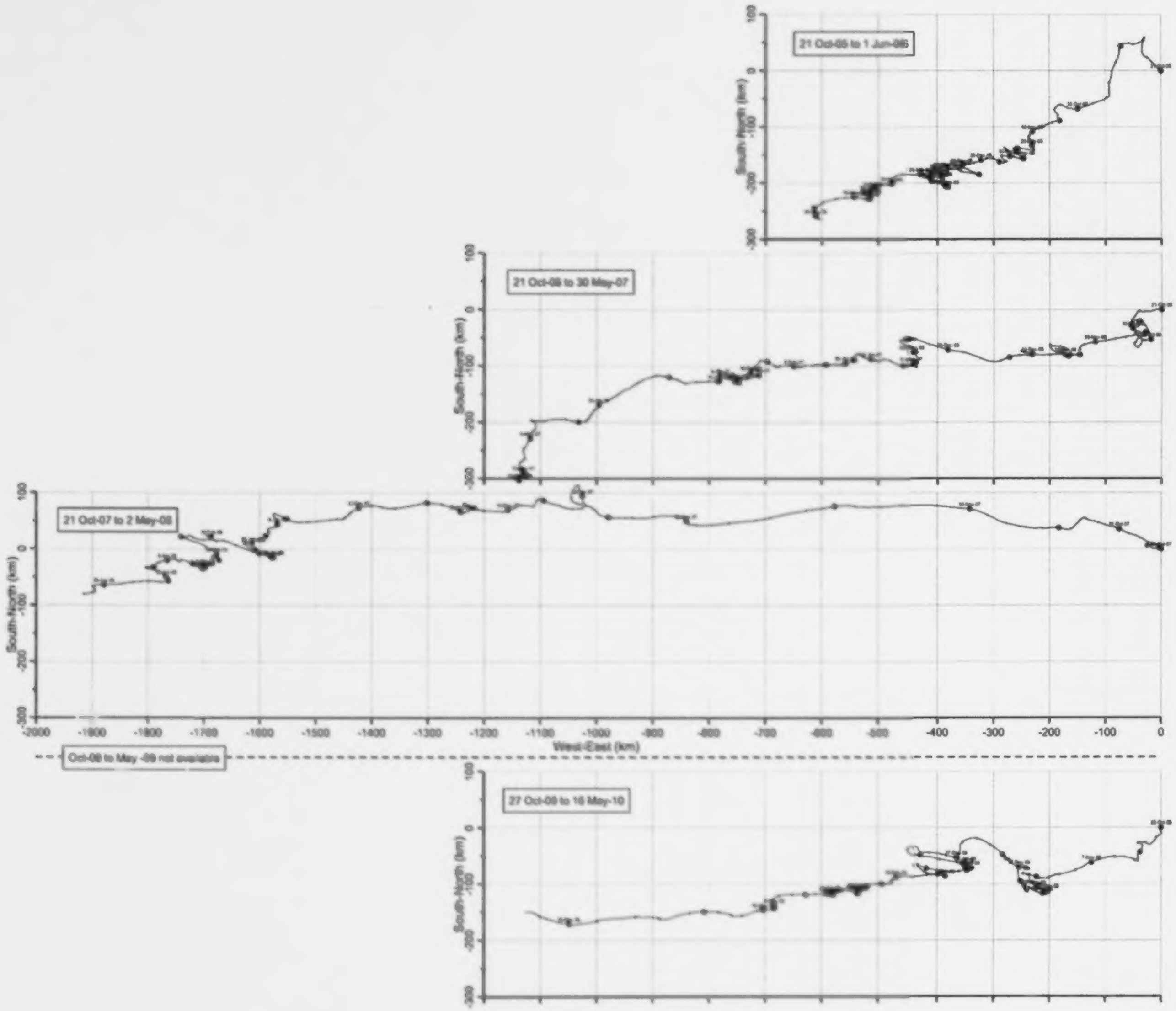
- The summertime clearance of sea ice from the shelf areas varied greatly over the 5-year period.
- Coverage was greater than the long-term median in some years, less than the median in others.
- The years of earliest clearance were the same for all shelf areas, 2007 and 2010.
- The year of latest clearance was 2008 in eastern Amundsen Gulf, and 2006 further west.
- The range in clearing dates over the five summers exceeded two months.
- There are 30-year trends towards a reduced presence of sea ice in each of the areas.
- Observed change is most likely a consequence of natural variation around a stable state, because the slopes of computed trend lines are indistinguishable from zero at 95% confidence.

Sea-ice Drift

Sea-ice drift is indicative of the mechanisms and timing of ecologically important ice clearance events on the Beaufort continental shelf, year-round. In winter, these events correspond to opening and closing of the flaw lead; in spring and summer, they herald the beginning of the open-water period. Figure 7 shows progressive vectors of sea-ice drift during four winters (2005-2010). The data were acquired via sonar, measuring ice velocity from a fixed location at the seabed. The sonar was positioned in the Kugmallit Valley north of Richards Island, about halfway to the shelf edge (Fig. 1). Failure of the sonar placed in October 2008 precluded the acquisition of ice-drift data for that winter.

A progressive vector is the summation of all measured movements and represents the total displacement of the ice during the winter. Net ice drift during winter (October through May) differed by a factor of three between 2005 and 2010. The greatest displacement, almost 2000 km, occurred during the winter of 2007-08, the year of greatest anomaly in surface air pressure (Fig. 2). The direction of drift also varied. During 2005-06, ice drifted roughly parallel to shore (WSW), a heading not conducive to opening the flaw lead. Drift in other years was more westerly, and more conducive to early opening of the ecologically important flaw lead in the eastern Beaufort Sea. These data on wintertime ice drift suggest that ice would have cleared from the eastern Beaufort Sea earliest in the spring of 2008, and that ice cover would have been at a minimum during the subsequent summer. The ice-cover data presented in Figure 6 show this to have been true. However, conditions on the shelf in the summer of 2010 were similar to those in 2008, despite much less total westward ice drift. Close inspection of the ice progressive vectors provides the explanation: ice was relatively inactive during the winter of 2009-10, but there was a compensating and very strong westward push, by 500 km, in May 2010. Wind anomalies clearly have a strong impact on ice conditions in the southern Beaufort Sea, and by inference strong impact on regional ecology.

Figure 7. Progressive vectors of sea-ice drift during four winters, 2005-2010. Crosses delineate each 1-day interval with red circles every five days. Data were acquired by Doppler sonar on the 35 m isobath in Kugmallit Valley. Data from DFO (H. Melling).



Ice Thickness on the Mackenzie Shelf

Ice concentration is the fraction of the sea surface covered by sea ice of any thickness. Marine life is sensitive to characteristics of the ice cover at a scale much finer than easily mapped by satellite. Birds and marine mammals can exploit small leads for feeding and breathing. Seals can easily break through new ice for breathing while Bowhead and Walrus can surface to breathe through ice 30 cm or more in thickness (George et al. 1989).

Ice profiling sonar can acquire an accurate and detailed view of the sectional geometry and thickness distribution of sea ice. Such sonar has been maintained on moorings on the Mackenzie Shelf for the last 20 years (H. Melling, pers. comm.). The site providing data used here is in the Kugmallit Valley about halfway between the coast and the shelf edge. This site has been dominated by first-year pack ice with incursions of old ice, short-lived and only in a few years. The long-term variation in ice thickness at this site was reviewed by Melling et al. (2005). Working with 12 years of observations, the authors concluded that there were no long-term trends in the thickness and character of sea ice over the Mackenzie continental shelf. Their analysis has recently been updated and now includes the most recent 19 years of data. This conclusion has not changed and is supported by the analysis of charted ice concentrations for the Mackenzie Shelf (presented earlier) suggesting insignificant trends in ice conditions over the shelf during the last 30 years. Although multi-year ice is now very clearly less common in the Arctic Ocean than two decades ago, the first-year ice in the Beaufort Sea does not appear to be responding in the same way to the suite of factors contributing to the loss of multi-year ice.

Ice thickness from the Kugmallit Valley mooring site on the Mackenzie Shelf is displayed for 2005-2010 in Figure 8. Variables are evaluated for 5-day blocks of data throughout the year. The variables selected are: average ice thickness (estimated from measured draft), time faction when ice was thinner than 5 cm (essentially the fraction of open water), and the time fraction when ice was thinner than 35 cm (approximately the fraction of mammal friendly ice cover). As expected, ice conditions varied widely during the five years. Ice was lightest during 2007-2008, with ice thickness less than 2 m for most of the winter, an appreciable presence of thin first-year ice until the end of December and an early clearance of ice at the beginning of May. All these attributes are consistent with the rapid westward drift of ice during the same winter (Fig. 7). Ice clearance was latest in 2006 (i.e., end of July), following the winter of least westward ice drift. The thickest ice, 3-5 m, appeared in May-June of 2009, although ice was thickest on average during the 2005-2006 winter. The winter with most frequent occurrence of thin ice was 2006-2007.

In most winters, abrupt declines in ice thickness from late winter maxima indicate that the loss of ice from the southeastern Beaufort Sea occurred via advection – ice was blown away to the west before either it or its snow cover could melt. This situation implies that there was relatively little addition of ice-melt to shelf waters in these years. In 2006 ice clearance was late; there was a progressive decline in ice thickness with negligible open water over an interval of six weeks. During this summer, it is likely that ice melt deposited a 2-3 m layer of fresh water over the continental shelf.

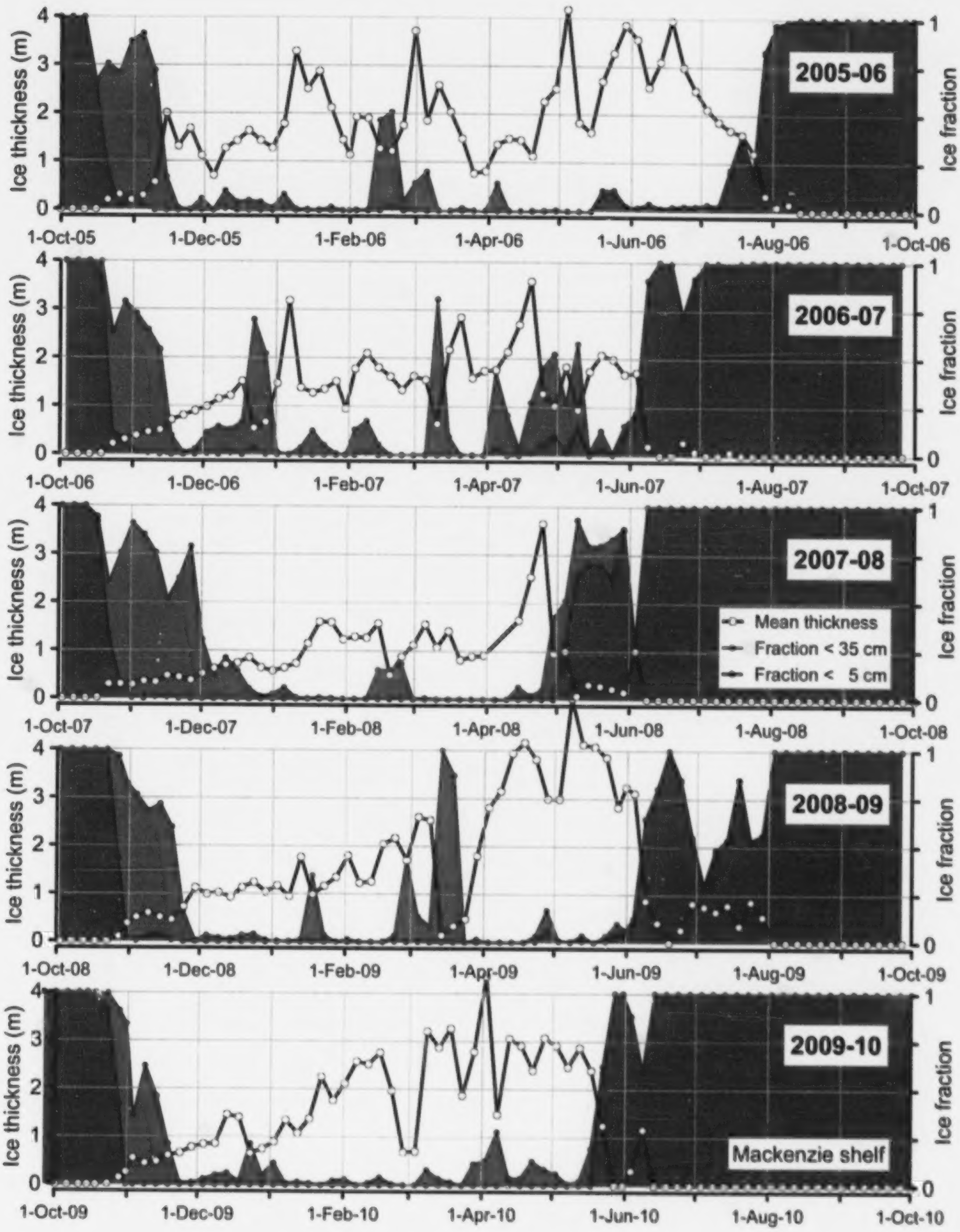


Figure 8. Mean ice thickness, fraction of ice less than 5 cm and ice fraction less than 35 cm on the Mackenzie Shelf between 2005 and 2010. Data were acquired by Doppler sonar moored at the 55 m isobath in Kugmallit Valley. Data from DFO (H. Melling).

Ocean Waters on the Mackenzie Shelf

Bottom Current

The direction and speed of bottom current is indicative of upwelling that can deliver dense nutrient-rich seawater to support primary production on the continental shelf. The DFO-operated sonar at the mid shelf, north of Kugmallit Bay, also provides data on ocean current. Ocean current data from 8 m above the seabed are presented in Figure 9 as progressive vectors for 12-month intervals (October through September).

The general tendency of the near-bottom current at mid shelf during the last five years has been shoreward, a direction approximately 90° to the left of that of surface currents/ice drift. This is indicative of upwelling deeper water, a normal occurrence on the Mackenzie Shelf (Williams et al. 2008). The annual displacement of bottom water here measures hundreds of kilometers, although the site is only 100 km from shore. This disparity illustrates that Kugmallit Valley is a conduit capable of delivering nutrient-rich water from offshore to a wide area of the inner shelf. The deliveries were greatly enhanced by prolonged east-wind anomalies during the reporting period.

Bottom Salinity

Upwelling delivers dense nutrient-rich seawater which may ultimately reach the photic zone and support primary production on the continental shelf. The salinity of bottom water is a readily measured indicator of upwelling on the continental shelf, and a proxy variable for dissolved nutrient concentration that cannot yet be measured by autonomous instruments. Figure 10 displays salinity within a few meters of the seabed from instruments on moorings at three locations on the Mackenzie Shelf: the shelf edge, the mid shelf and near the edge of fast ice.

Episodes of increased salinity at these sites mark the arrival of upwelled water from greater depth and further offshore. There are more events at the shelf edge (Fig. 10, blue curve) than closer to shore, indicating that it is only relatively infrequent sustained forcing by wind that delivers substantially saltier and nutrient-rich water to the ecosystems of the middle and inner shelf.

An event of unprecedented (since the mid 1970s) intensity and duration occurred between November 2007 and February 2008. The salinity of bottom water exceeded 34.5 ppt at the middle and outer shelf for about two months at this time. On the inner shelf (Fig. 10, red curve), the bottom salinity was between 35 and 36.5 ppt during the same interval. The maximum salinity of water in the Canada Basin is less than 35, and salinity is close to that value only below 500-m depth. Therefore, not only was upwelling very intense, but brine rejection during ice growth must have contributed to these very high anomalies. The extremely fast westward drift of sea ice during the winter of 2007-08 (Fig. 7) that continually exposed the sea surface to new ice growth, will have been a strong contributor to the injection of brine into the coastal ocean at this time. There is a second strong and prolonged upwelling of deep water at the shelf edge again in May-June 2010, although this did not appear to move water to the mid shelf. This immediately follows the 500-km westward displacement of ice in May 2010 noted earlier.

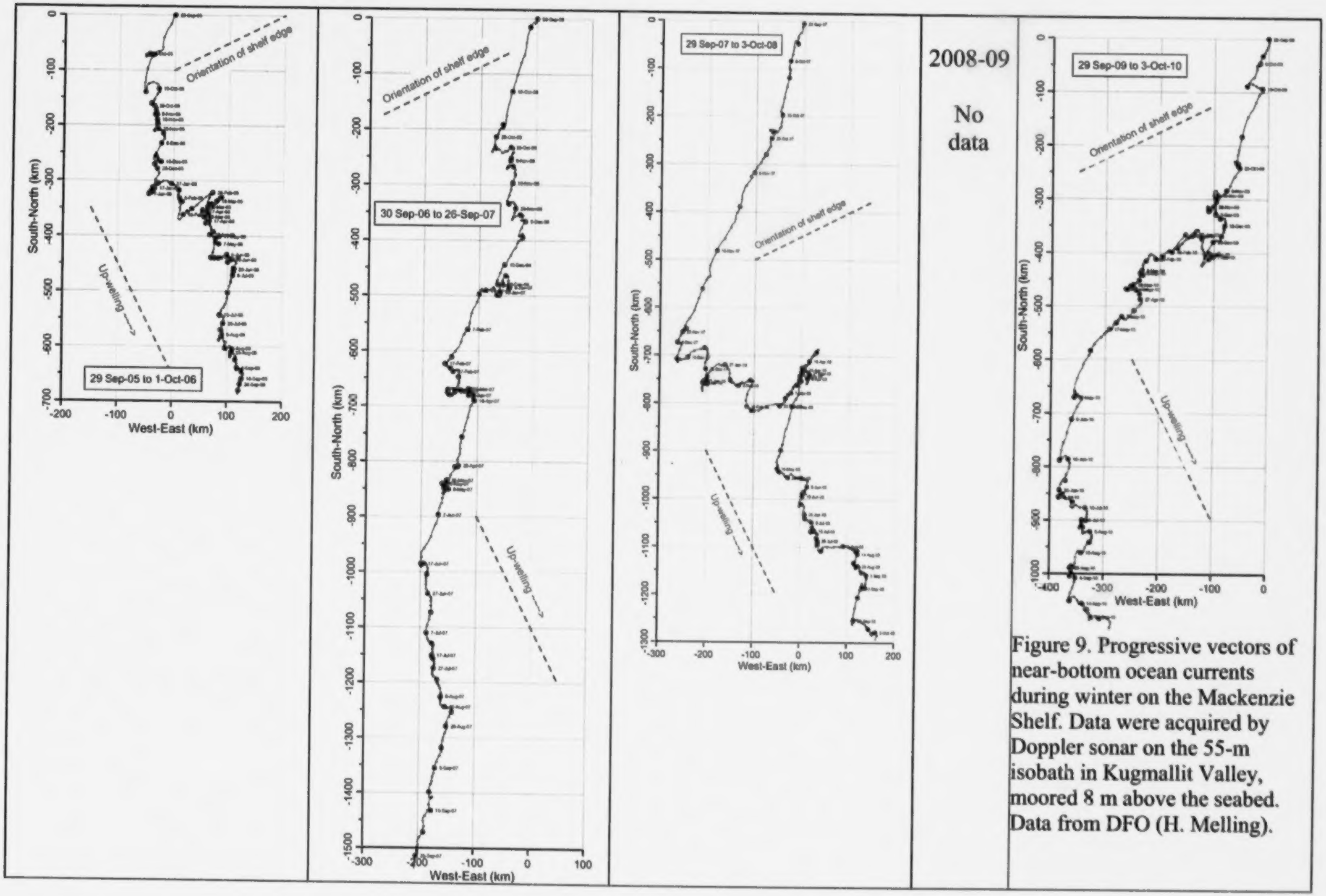


Figure 9. Progressive vectors of near-bottom ocean currents during winter on the Mackenzie Shelf. Data were acquired by Doppler sonar on the 55-m isobath in Kugmallit Valley, moored 8 m above the seabed. Data from DFO (H. Melling).

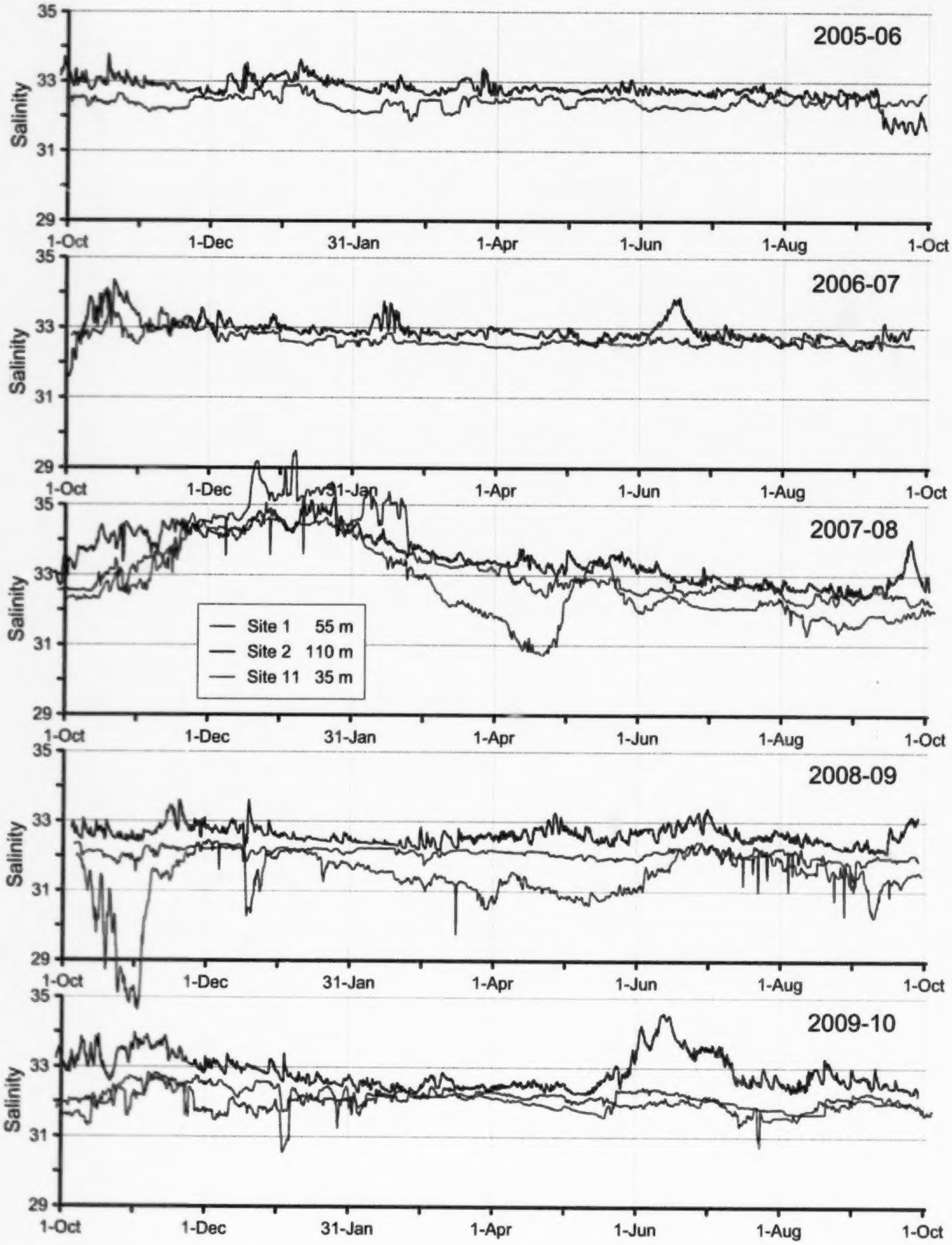


Figure 10. Salinity of water near the seabed at locations near the edge (Site 2: 110 m), middle (Site 1: 55 m) and inner (Site 11: 35 m) Mackenzie Shelf. Data from DFO (H. Melling).

Surface Salinity

The salinity of surface water is a readily mapped indicator of water-column stability and of the local presence of fresh water derived from river discharge or melting ice. Low surface salinity in summer is commonly linked to high stability and low concentrations of dissolved nutrients and sometimes to high turbidity. Between 2005 and 2010, the properties of near-surface water have been measured via a seawater through-flow system installed on the Canadian Coast Guard Ship (CCGS) Sir Wilfrid Laurier. A Western Arctic Patrol is conducted annually, completing a homebound transit west across the southern Beaufort Sea in early October. Surface salinity and temperature from the transits are shown in Figure 11.

Once again these surveys reveal large inter-annual variation. Surface salinity over the Mackenzie Shelf was lowest in 2006 when a weak wind regime was unable to drive river discharge elsewhere. In 2007 and 2010, surface salinity over the shelf was much higher; lower values were well offshore and to the west, indicating where the strong east winds during these summers had pushed the river water. This distribution pattern of salinity, with values highest near the coast and lowest offshore, is the opposite of the normal pattern. Much of the fresh water inventory was no doubt transferred to the Beaufort Gyre in these years leaving very little river discharge water and ice-melt water stored on the continental shelf. This export, in combination with strong upwelling, contributed to setting a new record maximum value for shelf salinity in the early winter of 2007-2008.

The explanation of the temperature maps is not so straight-forward. Typically, water of low salinity floats at the surface and is preferentially warmed by the sun in summer. In contrast, more salty water upwelled to the surface is cold, having been isolated from insolation. This correlation is well represented by the maps for 2006 and 2007 (Fig. 11). However, water upwelled in early summer is able to accumulate solar energy and this may explain the contrast between conditions in 2010 and 2007.

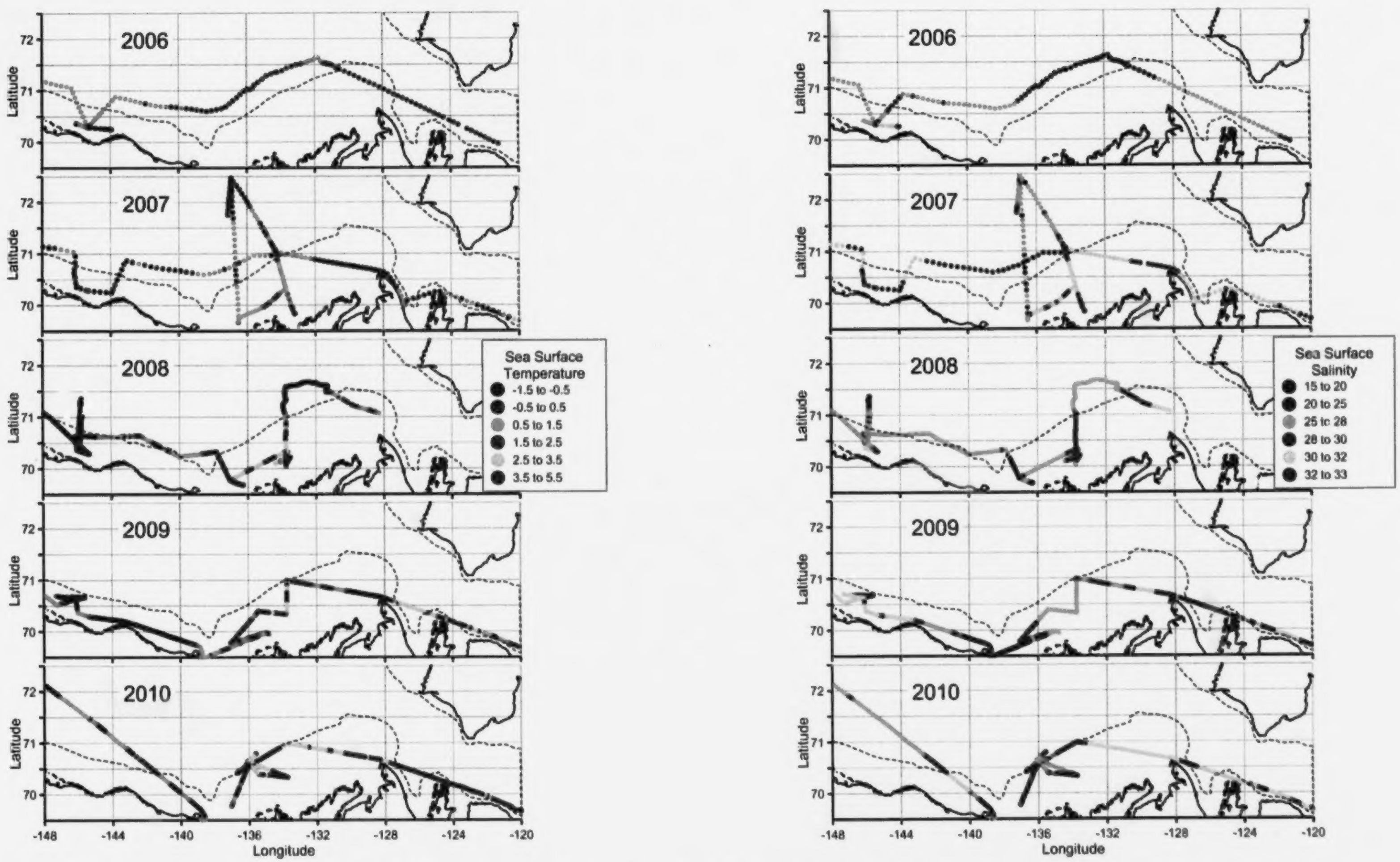


Figure 11. Sea-surface temperature (left) and salinity (right) along the path of CCGS Sir Wilfrid Laurier in late September-early October. Data from DFO (H. Melling).

2. RECENT CHANGES IN THE BEAUFORT GYRE

North of the Canadian and Alaskan Beaufort Shelves lie the 3800 m deep waters of the southern Canada Basin. There, anticyclonic wind and sea-ice motion force convergent Ekman transport, resulting in an accumulation of relatively fresh polar surface waters that form an anti-cyclonic gyre called the Beaufort Gyre. The top 400 m of this gyre contain layers of water of various origin that together form the strongly stratified arctic halocline. The surface waters are strongly influenced by the Eurasian and North American rivers that drain into the Arctic. Beneath these, between approximately 150 and 250 m deep are layers of Pacific-origin water that has flowed through the Bering Strait across the Chukchi Sea shelf and finally crossed the shelf break into the Canada Basin. Beneath the Pacific Origin waters, forming the base of the halocline, are waters of Atlantic origin. These Atlantic waters enter the Arctic Ocean through Fram Strait and the Barents Sea and flow around the Eurasian basins of the Arctic before reaching the Canada Basin. At the base of the halocline is the temperature maximum of the Atlantic origin water that has flowed through Fram Strait.

Since 2002, Joint Ocean Ice Studies (JOIS) has mounted an annual expedition to the Beaufort Gyre to monitor the oceanographic conditions there, including ice cover, the sources, accumulation and release of freshwater in the gyre, changes in the Pacific and Atlantic origin water masses, ocean acidification and the structure and function of the lower trophic levels of the ecosystem. Below is a summary of the observed changes since approximately 2003.

Ice cover

There has been a dramatic reduction in the extent and age of multi-year sea ice in the Arctic Ocean since the mid 1990s, including the northern portion of the Beaufort Sea LOMA (Fig. 12). The younger, thinner ice is more responsive to wind-stress, thereby affecting the cohesiveness of the ice pack. The loss of the thick Arctic ice pack impacts ocean circulation and salinity with consequences for the marine food web.

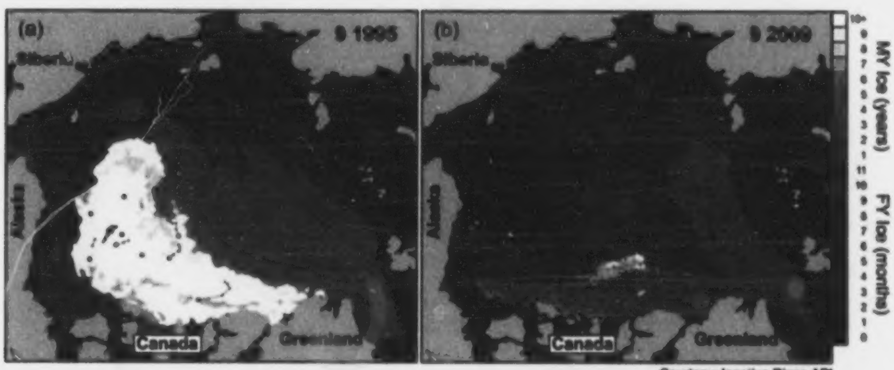


Figure 12. Age of multi- (MY) and first-(FY) year Arctic ice pack in September 1995 (a) and 2009 (b) showing the large change in the fraction of multi-year ice. The red dots and their trails are the paths of buoys drifting with the ice. Courtesy of Ignatius Rigor, Applied Physics Laboratory, University of Washington.

Fresh water content

Changes in the fresh water content of the Beaufort gyre has been assess since the 1950s, with the 1990s and 2000s being significantly fresher than 1950-1980 (Proshutinsky et al. 2009). An increase in anticylonic wind-stress over the Beaufort Gyre associated with the positive phase of the Arctic Ocean Oscillation has lead to an accumulation of fresh water in the Beaufort Gyre in recent years. The total fresh water present in the water column relative to a salinity of 34.8 psu is shown in Figure 13. The fresh water fraction of water, at a particular salinity, is calculated by considering it a mixture of fresh water and water of salinity 34.8 psu. This fraction is then integrated from the depth of the 34.8 isohaline to the surface. The amount of fresh water increased rapidly over the area shown, from an average of 18.8 m in 2006 to 22.4 m in 2010 (Fig. 13). The positive freshening trend includes significant interannual and regional variation (Proshutinsky et al. 2009).

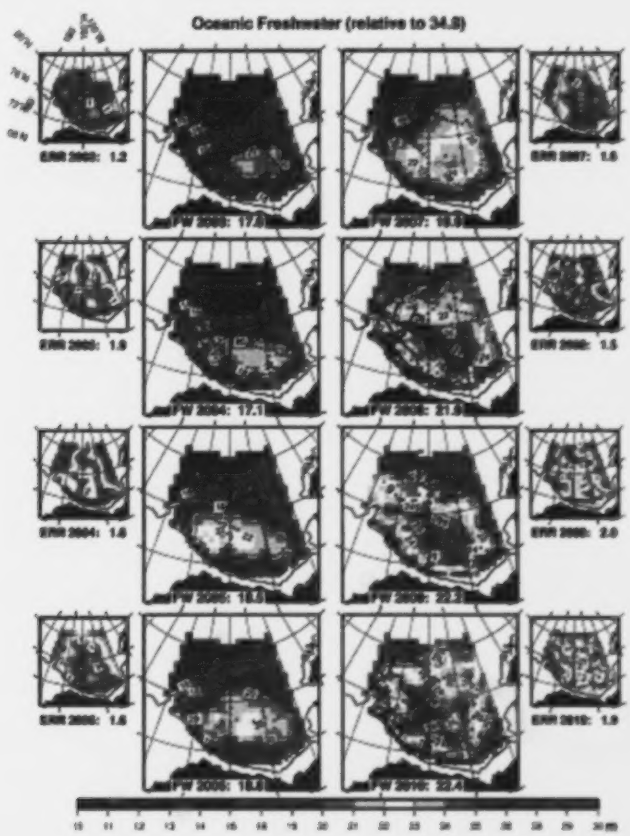


Figure 13. Accumulation of fresh water (relative to salinity 34.8 psu) in the Beaufort Gyre between 2003 and 2010. Contour lines indicate the amount of fresh water in meters (m). The average amount of fresh water (m) for the area contoured is given at the base of each plot. The smaller plots are estimates of the error in the fresh water calculation away from the data points (black dots in larger figures).

Recent changes have also been observed in the surface waters of the Beaufort Gyre. Surface water salinity in the Beaufort Gyre has shown a freshening trend since 2003 (Fig. 14). This freshening has been linked to fresh water input due to sea-ice melt (M. Yamamoto-Kawai, pers. comm.).

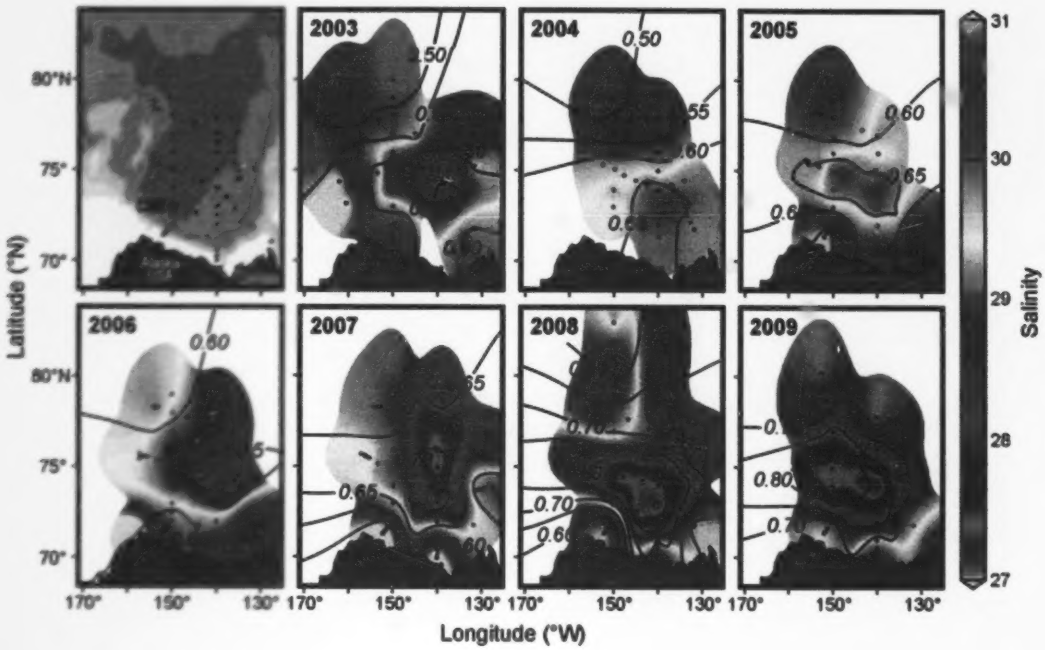


Figure 14. Sea surface salinity of the Beaufort Gyre from 2003 to 2009. Contours are surface dynamic height relative to a reference depth of 800 m and show the strengthening of the Beaufort Gyre (from McLaughlin and Carmack 2010).

Increasing stratification

McLaughlin and Carmack (2010) show, from 2003-2009 data, that the increase in both Ekman convergence and fresh water input in the Beaufort Gyre associated with sea ice retreat and melt, have increased the stratification and depth of the upper halocline beneath the seasonal mixed layer. Figure 15a shows the buoyancy frequency due to salt stratification at the top of the halocline underneath the mixed layer in the Canada Basin and demonstrates the increase in stratification over time.

The changes in buoyancy accelerated from 2007–2009 when salt stratification below the seasonal mixed layer increased about 25% (Fig. 15a). The increased stratification further constrains vertical heat flux and the winter renewal of nutrients into the euphotic zone. One consequence of increased Ekman convergence is that both the depth of the nitracline (i.e., the depth where nitrate concentrations begin to increase from zero) and the depth of the chlorophyll maximum (which occurs slightly below the depth of the nitracline as here both nitrate and light are sufficient to allow primary production) have increased (Fig. 15b).

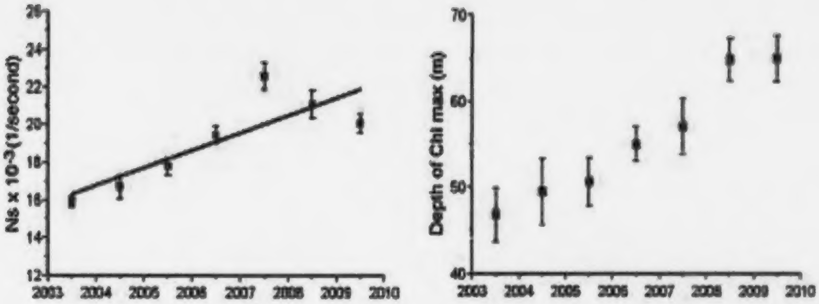


Figure 15. Buoyancy frequency at the top of the halocline underneath the mixed layer (a) and increasing depth of chlorophyll maximum (b) in the Beaufort Gyre, 2003 to 2009 (from McLaughlin and Carmack 2010). An increase in buoyancy frequency indicates increased stratification at the base of the seasonal mixed layer.

A schematic of changes in the Beaufort Gyre between 2003 and 2009 is shown in Figure 16. In this schematic, melting of thick multi-year ice in the Canada Basin produces fresher surface waters and increases stratification beneath the surface mixed layer reducing upward nitrate (NO_3) flux to the mixed layer. Along with the melting of multi-year ice comes a thinner, more mobile ice pack with reduced summer extent that allows the prevailing anticyclonic winds to drive larger Ekman convergence in the Beaufort Gyre. The increased convergence both strengthens the Beaufort Gyre and deepens the base of the mixed layer, the top of the nitracline and the depth of the chlorophyll maximum.

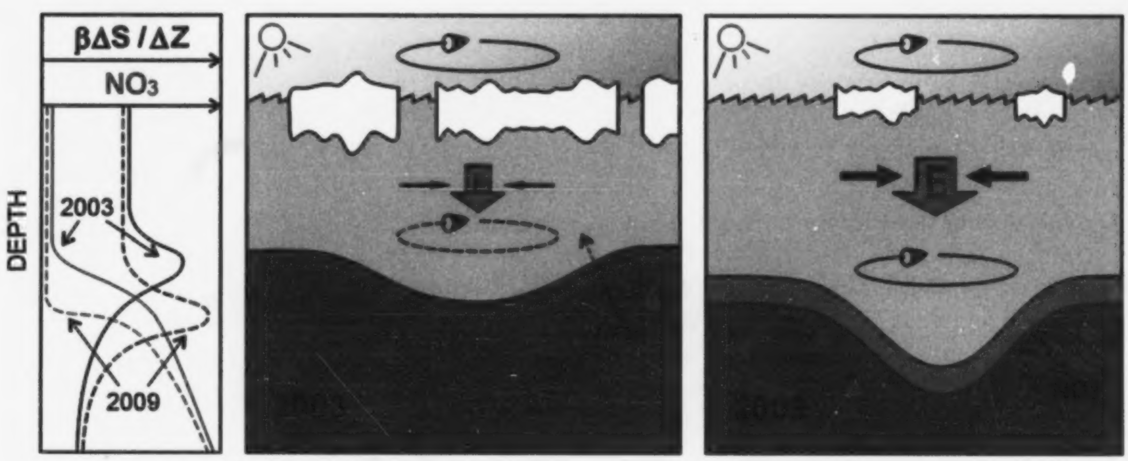


Figure 16. Schematic of ecosystem shifts in the Beaufort Gyre due reduction of sea ice (from McLaughlin and Carmack 2010).

The increased stratification (Fig. 15) and decrease in upper layer nutrient concentrations has resulted in an increase in the number of pico-sized plankton and a decrease in nano-sized plankton (Li et al. 2009). This trend of increasing summer picoplankton abundance in the upper water column of the Canada Basin was recorded in the previous 5 years. In 2009, picoplankton sampled in the late summer and early autumn showed evidence of

continued increase, but only for the heterotrophic component, namely the bacteria. In contrast, an apparent departure from the trend for picophytoplankton in 2009 indicates interannual variability and strong seasonality in the photosynthetic component.

3. OCEAN ACIDIFICATION - EVIDENCE FROM THE CANADIAN BASIN

Ocean acidification was predicted to begin impacting the Arctic Ocean within the next decade (Steinacher et al. 2009). However, evidence of acidification (Yamamoto-Kawai et al. 2009) and negative impact on key marine species (e.g., pelagic mollusk (*Limacina helicina*), Comeau et al. 2009; Lischka et al. 2011)) have already been detected in the Arctic.

When CO_2 is taken up by the ocean it reacts with water to form carbonic acid. The formation of carbonic acid lowers the pH resulting in ocean acidification that is accompanied by the reduction in the saturation state (omega, Ω) of calcium carbonate ($CaCO_3$). The two most common forms of $CaCO_3$ produced by marine organisms are calcite and aragonite. Aragonite (found particularly in corals and mollusks) is 1.5 more soluble than calcite (e.g., crustaceans) (Millero 1996), and is therefore more sensitive to ocean acidification. When the value of Ω is calculated for either aragonite (Ωa) or calcite (Ωc), a value <1 indicates waters undersaturated with respect to that specific form of $CaCO_3$. When undersaturation occurs, it can become difficult for marine organisms to maintain and/or grow their $CaCO_3$ shells and skeletons. The impact of undersaturation will vary between species, depending on the specific form of $CaCO_3$ they require and the type of undersaturation that is occurring (i.e., Ωa or Ωc).

Surveys conducted in 1997 in the Arctic Ocean, which include a portion of the Canada Basin within the Beaufort Sea LOMA, found that surface waters were oversaturated (i.e., $\Omega > 1$) with respect to $CaCO_3$, such that conditions were favorable for calcifying marine organisms (Jutterström and Anderson 2005). However, when the same area was surveyed again in 2008, surface waters had become undersaturated, specifically in respect to aragonite $CaCO_3$ (i.e., $\Omega a < 1$, Yamamoto-Kawai et al. 2009), with minimum values near the centre of the Beaufort Gyre where Ωa was ~0.8.

Surface water Ωa decreased by 0.4 over 10 years (ca. 1997 to 2008) in the Canada Basin. This decrease is six times higher than decreases observed in tropical waters over the same time period (i.e., 0.07, ALOHA station Hawaii; Doney et al. 2009). Although the aragonite saturation state is undergoing rapid changes in the Arctic, the less soluble calcite was still marginally oversaturated (Ωc 1.1-2.0) in the Canada Basin surface waters in 2008 (Yamamoto-Kawai et al. 2011).

Several processes and oceanographic variables can impact the saturation state of $CaCO_3$. Pressure, temperature, salinity, anthropogenic inputs and respiration/remineralization of CO_2, freshwater dynamics and ocean mixing can all be considered when addressing shifts in $CaCO_3$ saturation states. Yamamoto-Kawai et al. (2011) have identified the relative contribution of several factors to the recently observed undersaturation of aragonite in the surface waters of the Canada Basin (Fig. 17). Increases in atmospheric CO_2 since the

preindustrial period and recent sea-ice melt both lowered Ωa. The impact of sea-ice melt occurred in two ways. Firstly, the sea-ice melt contributed to the dilution of surface waters, and secondly, enhanced gas exchange (air-sea disequilibrium state) lowered Ωa as a result of longer ice-free periods in combination with increased areas of open water due to sea-ice melt. Decreases in Ωa were counteracted by surface water warming in the Canada Basin (Fig. 17).

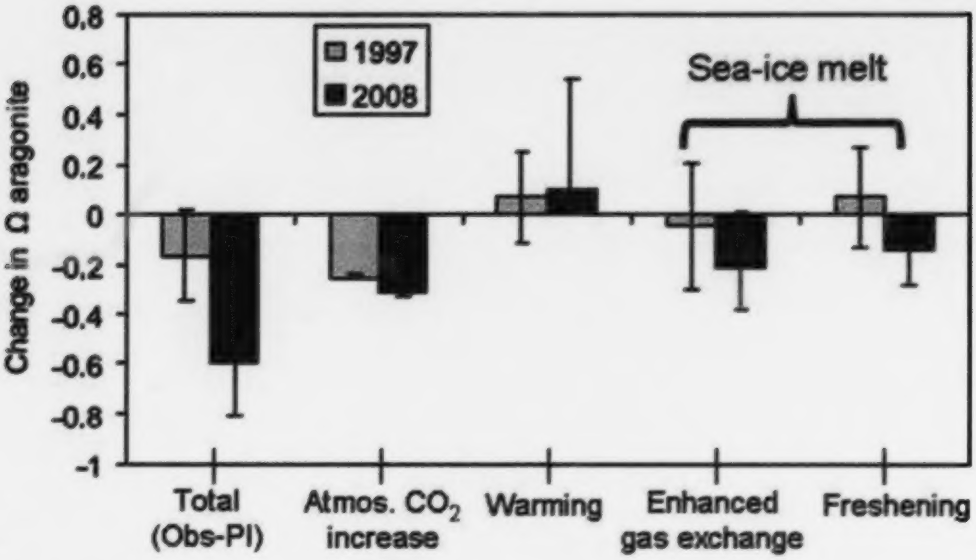


Figure 17. Mean changes in Ωa in Canada Basin surface waters caused by increases in atmospheric CO_2, surface water warming, enhanced gas exchange and freshening by sea-ice melt dilution. Total changes represent observed values in 1997 and 2008 relative to preindustrial (PI) values. Figure adapted from Yamamoto-Kawai et al. (2011).

Although recent measurements of $CaCO_3$ saturation states are for offshore waters of the LOMA, it is expected that the effects of ocean acidification will also be important on the shelf via upwelling of nutrient-rich, but low Ωa, Pacific-origin water across the shelf break. The so-called Pacific Winter Water forms a layer in the Canada Basin between 125 and 225 m deep that is undersaturated with respect to aragonite, reaching a minimum of Ωa ~0.75 at ~175 m (Yamamoto-Kawai et al. 2009). This undersaturation is due to a combination of remineralisation of organic matter from the productive Bering and Chukchi Sea shelves and from increases in atmospheric CO_2 (Yamamoto-Kawai et al. 2009). As the Pacific Winter Water lies just below the Beaufort shelf-break depth of 70-90 m, upwelling across the shelf break is expected during upwelling-favourable surface stress (W. Williams, pers. comm.). In addition, since 1997, there has been a 75% average increase in upwelling favourable surface-stress at the shelf break of the southern Beaufort Sea (based on satellite-derived wind, ice-concentration and ice velocity) that appears to be due to a combination of an increase in upwelling favourable wind-stress over open water and an increase in the apparent responsiveness of the ice to upwelling favourable wind. The combination of enhanced atmospheric CO_2 combined with enhanced

upwelling will increase the frequency and/or area of the shelf that is affected by undersaturated waters, as has been proposed for mid-latitude shelves (Feely et al. 2008).

4. INDICATORS AND IMPLICATIONS OF DISTINCT ZOOPLANKTON ASSEMBLAGES IN THE BEAUFORT SEA LOMA

The first thorough investigations of zooplankton distribution in the Beaufort Sea LOMA focused on the coastal area and inner shelf (Grainger 1975; Grainger and Grohe 1975). Mackenzie River flow, including the extent of the plume, and oceanographic circulation patterns were identified as key factors influencing zooplankton composition and distribution. Recent zooplankton studies within the LOMA have identified distinct zooplankton assemblages during the summer (July/August 2005 and 2006, Walkusz et al. 2010) and fall (September/October 2002, Darnis et al. 2008) in the near and offshore regions (Fig. 18). The results of these two studies are presented in this section.

Zooplankton diversity was higher during the summer than fall study with 99 taxa identified within the coastal region under the influence of the Mackenzie River plume (Walkusz et al. 2010). In the fall, only 49 zooplankton taxa were identified with over 95% of the zooplankton represented by only 8 copepod taxa (Darnis et al. 2008). Differences in mesh size used during the summer and fall study (153 versus 200 µm, respectively), seasonal life history of zooplankton assemblages, inter-annual variability and regional differences may have contributed to the differences in taxonomic diversity observed.

During the summer study (Walkusz et al. 2010), three cross-shelf zooplankton assemblages could be identified and were labeled as the Intense plume, Diffuse plume and Oceanic assemblages. All stations except TOK11 (Fig. 18a) had a surface layer of brackish warm water representative of the plume. The Diffuse plume zone encompassed the frontal zone between the Mackenzie River plume and marine waters and had the most diverse zooplankton assemblage of the three zones. In the Diffuse zone, freshwater and marine zooplankton can coexist thereby enhancing observed taxonomic diversity. The Oceanic zone had the greatest overall zooplankton abundance and biomass. The plume front is an active oceanographic feature undergoing constant modification. Although the river plume clearly influences zooplankton composition, distribution, abundance and biomass, it should be understood that boundaries can not be strictly defined for the three cross-shelf assemblages from an inter- or intra-annual perspective.

The copepod *Pseudocalanus* spp. was a key identifier of the Intense and Diffuse zones. In 2006, when the Garry transect was sampled (GAR stations, Fig 18a), the brackish zooplankter, *Limnocalanus macrurus* was also identified as a key species in the two nearshore zones. Therefore, these nearshore zones of the LOMA contain zooplankton that is a key component of larval fish and Bowhead diets. The Oceanic zone was differentiated by the presence of typical marine species, including *Calanus glacialis* and *C. hyperboreus*, with few *Pseudocalanus* spp., consistent with the results of the fall study.

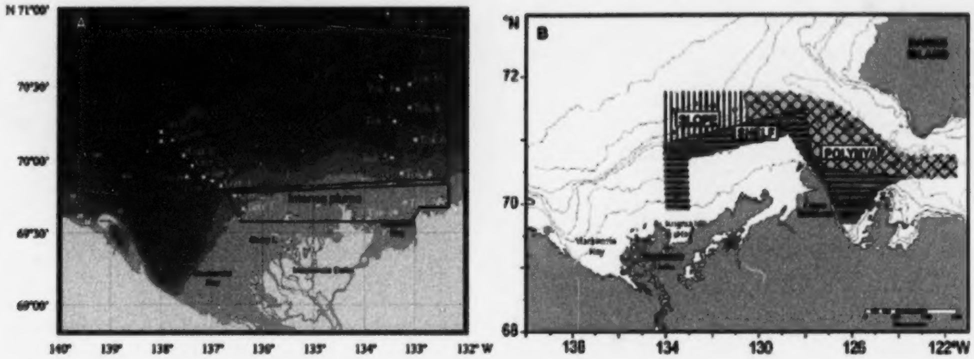


Figure 18. Location of three distinct zooplankton assemblages on the shelf and slope of the Beaufort Sea LOMA during summer (A) and fall (B). Figures adapted from Walkusz et al. (2010) and Darnis et al. (2008).

The fall 2002 zooplankton study in the LOMA (Darnis et al. 2008) was focused eastward of the summer study, although stations offshore of Kugmallit Bay overlapped between the two studies (Fig. 18). Three distinct fall zooplankton assemblages could be identified and were labeled as Shelf, Polynya and Slope assemblages. Franklin Bay is included in the Shelf zone and the Polynya zone encompasses the Cape Bathurst polynya and a portion of the Amundsen Gulf (Fig. 18b).

The Shelf zone was dominated by herbivorous zooplankton, in particular *Pseudocalanus* spp. Omnivorous and carnivorous species were more abundant in the Polynya and Slope zones, although their biomass remained lower than herbivorous species. *Pseudocalanus* spp. was again a key taxon distinguishing the zooplankton assemblages, being dominant on the Shelf, abundant in the Polynya but scarce in the Slope zone. The nauplii and copepodites of *Pseudocalanus* spp. are key prey of larval and juvenile Arctic Cod (*Boreogadus saida*) making the Shelf zone favorable spawning grounds for this important fish within arctic food webs.

The Shelf assemblage had lower diversity and species richness than the other two zones, whereas zooplankton biomass was highest in the Polynya zone due to the co-occurrence of large species (e.g., *C. glacialis* and *C. hyperboreus*). Overall the distribution of zooplankton in the fall was linked to water depth and duration of ice cover (defined in this study as period of time with <50% ice; Darnis et al. 2008). In deeper waters distinct water masses can be present (i.e., polar mixed, Pacific and/or Atlantic water layers) supporting enhanced diversity. In addition, deep waters are critical for overwinter survival of large pelagic copepods in the LOMA, explaining the lower biomass of large copepods in the Shelf versus Polynya zone. Low temperatures and availability of phytoplankton due to the persistence of sea ice results in lower biomass of herbivorous zooplankton and consequently, omnivorous zooplankton that feed on the eggs and nauplii of the herbivores. In 2002, early ice retreat in the Polynya zone, combined with the presence of deep basins, could have contributed to the high zooplankton biomass in the Polynya relative to the other two zones.

These two studies clearly demonstrate that zooplankton zonation is a key feature of the Beaufort Sea LOMA. The distribution of zooplankton is tightly linked to Mackenzie River flow, oceanographic circulation, bathymetry and sea ice conditions. Shifts in the composition and distribution of zooplankton may be reflected in higher trophic levels including fishes, seals and whales. Climate changes resulting in an earlier opening of the Cape Bathurst Polynya or lengthening of the ice-free season in general, could impact the reproductive success and feeding dynamics of zooplankton within the LOMA.

5. LONG-TERM TRENDS AND RECENT STRESSORS FOR BOWHEAD

The Bering-Chukchi-Beaufort Bowhead populations overwinter in the Bering Sea and in spring, migrate into the Beaufort Sea and Amundsen Gulf for summer feeding. Bowhead arrive offshore in the Canadian Beaufort Sea in late May/early June and aggregate at a number of locations on the Beaufort Shelf and elsewhere, some remaining until late September or early October (Harwood et al. 2010).

Commercial whaling in the Beaufort Sea, from 1840 to 1907, depleted Bowhead from an estimated historic population between 10 400 and 23 000 down to ca. 3000 individuals (Zeh and Punt 2005). As of 2001, the Bering-Chukchi-Beaufort population was estimated to be between 8200 and 13 500 individuals, increasing at a rate of 3.4% per year between 1978 and 2001 (Zeh and Punt 2005). Aerial photographic surveys near Point Barrow Alaska in 2003-2005 arrived at population estimates consistent with the 2001 ice-based surveys (Koski et al. 2010). The most recent census of the Bering-Chukchi-Beaufort population was conducted in spring 2011 from which an updated population estimate will be available in the future.

Systematic aerial surveys conducted in late August 2007, 2008 and 2009 assessed the summer distribution of Bowhead in the Beaufort Sea LOMA, identifying nine geographic areas where Bowheads aggregated to feed in those years (Fig. 19, Harwood et al. 2010). The geographic areas used by Bowhead during the summer were consistent with observations from the 1980s. However, results from the recent surveys suggest that Bowhead may be aggregating two or more weeks earlier in the season than in the 1980s and that the stock size and/or usage of the southeast Beaufort Sea may be increasing. The LOMA is very important for Bowhead, with up to 50% of the Bering-Chukchi-Beaufort population estimated to be in the region at any one time during the feeding season. The most attractive area for Bowhead in the LOMA is the continental shelf, especially waters 20-50 m deep located offshore of the Tuktoyaktuk Peninsula (Fig. 19).

Bowhead do not aggregate in the same place each summer and move between different aggregation areas within the same feeding season (Quakenbush et al. 2010). These movements within and between years are thought to be linked to changes in oceanographic conditions which dictate the distribution of zooplankton, their primary prey. In 2008, ship-based sampling was coordinated with the Bowhead aerial survey so that zooplankton and oceanographic characteristics could be examined in close proximity to feeding Bowhead at a favoured feeding site offshore of Cape Bathurst. These areas had signatures of upwelling and dense aggregations of zooplankton which were located at

water depths below 40 m (Walkusz et al. submitted). Easterly along-shelf winds (see section 1) were favorable for upwelling, during the time of sampling, and concentrated the zooplankton at the preferred Bowhead feeding location. Relative to zooplankton assemblages sampled from the western side of the LOMA, the biomass and abundance of zooplankton near the feeding aggregation was twice as high and the energy content of the zooplankton was six-fold higher (Walkusz et al. submitted). These studies highlight the importance of understanding physical oceanography and subsequent trophic linkages for addressing mitigation and/or adaptation scenarios in the Beaufort Sea LOMA.

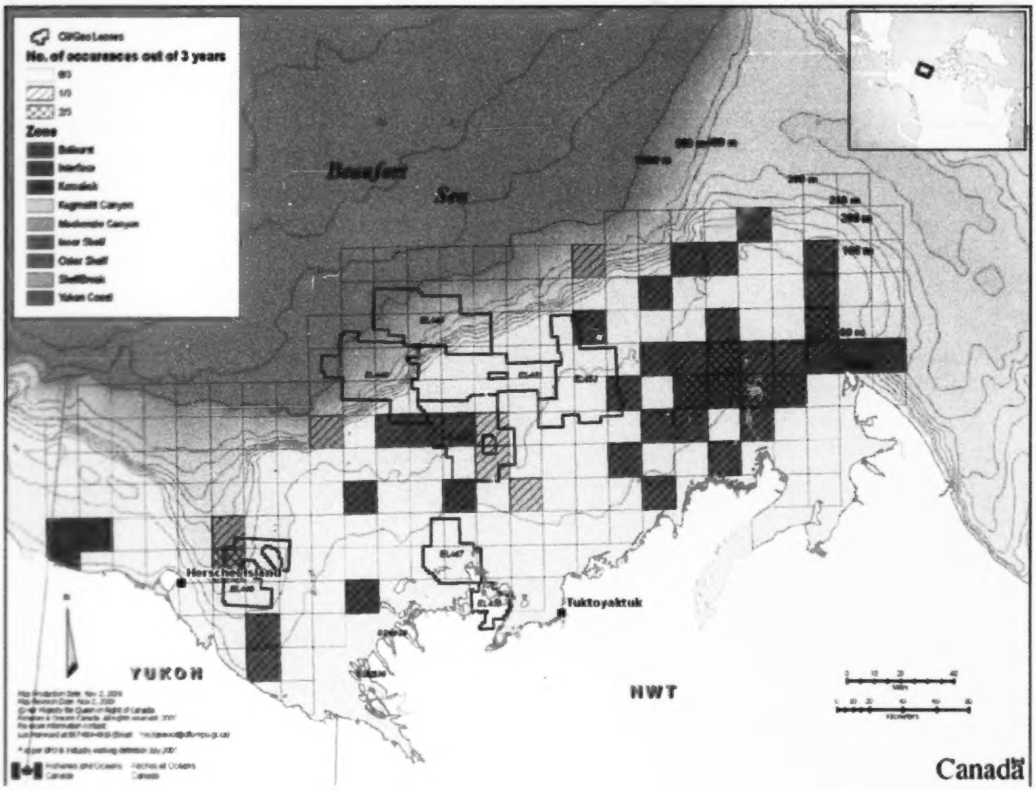


Figure 19. Nine geographic areas (zones) where Bowhead aggregated during summer (August 2007-2009) relative to oil/gas leases in the Beaufort Sea LOMA (from Harwood et al. 2010).

6. IMPORTANCE OF COMMUNITY MONITORING FOR ASSESSING BELUGA STATUS AND HEALTH

Beluga in the Beaufort Sea LOMA are part of the Eastern Beaufort Sea population, one of the largest Beluga populations in Canada. These whales are genetically distinct from other Beluga stocks found in Alaskan waters and their population is conservatively estimated at 40 000 animals (COSEWIC 2004). Beluga are a valuable subsistence and cultural resource in the ISR. The establishment of the Tarium Niryutait Marine Protected

Area (TNMPA) in the Beaufort Sea LOMA was based on Beluga aggregations within the Mackenzie Estuary (see section 9).

Since 1973, data and/or samples from Beluga landed during annual subsistence harvests have been collected by the Fisheries Joint Management Committee (FJMC) and DFO (Fig. 20). Local hunters participate as community-based monitors at seasonal whaling camps to collect hunt information and biological data and samples. The monitoring is conducted under the Beaufort Sea Beluga Management Plan. Hunters from Aklavik, Inuvik, Tuktoyaktuk and Paulatuk have been involved for many years. Recently, Beluga community monitoring has expanded to the communities of Sachs Harbour and Ulukhaktok (Holman). Hendrickson Island is a key monitoring site focusing on Beluga health. From 2000 to present, the annual community monitoring at Hendrickson Island has been led by DFO, in partnership with FJMC and the Northern Contaminants Program (NCP). Local monitors, together with researchers, collect samples such as reproductive material and tissues to test for diseases and contaminants (e.g., mercury).

Figure 20. Community-based monitoring during the Beluga hunt at Hendrickson Island. Photo DFO.

Community monitoring of Beluga in the LOMA has been successful at building a long-term dataset that can be used in many ways to assess the status and health of the Eastern Beaufort Sea stock. Below is a summary of recent key findings based on community monitoring datasets that are maintained by FJMC and DFO.

Sustainability of hunt

Over the last 10 years, on average, 99 Beluga per year have been landed by hunters within the LOMA (Table 2). The number of animals landed between 2000 and 2010 are significantly lower than the landings in the 1970s and 1980s ($p < 0.05$) but not significantly different than landings during the 1990s. Analyses of landings prior to 2000 found the current level of harvest to be sustainable based on the size and age structure of the catch (Harwood et al. 2002).

Table 2. Beaufort Sea LOMA Beluga harvest 2000-2010. (Data provided by FJMC)

YEAR	STRUCK	LOST	LANDED
2000	91	7	84
2001	96	1	95
2002	89	3	86
2003	123	10	116
2004	138	10	131
2005	108	2	106
2006	126	4	122
2007	83	0	83
2008	78	6	74
2009	102	6	98
2010	93	3	90
TOTAL	**1127**	**52**	**1085**

Age structure and growth of stock

Recent analysis of monitoring data found the median age of male and female Beluga in the Beaufort Sea LOMA to be 29 and 31 years, respectively, with the Eastern Beaufort Sea stock being significantly older than Beluga stocks in the Eastern Arctic (Luque and Ferguson 2010). A larger number of older animals are also being landed in the LOMA relative to hunts in the Eastern Arctic. The prevalence of older animals suggests that there is good recruitment of immature animals that remain for a longer period in the reproductive portion of the population (Luque and Ferguson 2006 and references therein). Therefore, assuming hunt data accurately represents population data, Beluga age structure within the LOMA suggests that the population is in a healthy condition.

Standard length of Beluga measured during community monitoring was used to determine growth characteristics for Beluga in the LOMA (Luque and Ferguson 2010). Male growth can be described by the Gompertz function in equation 1 and reach, on average, a maximum length of 432.3 ± 2.4 cm (Fig. 21, Luque and Ferguson 2009).

$$\text{Males: } 432.2e^{-1.16e^{-0.15x}} \qquad (1)$$

Similarly, female growth can be described by the Gompertz function in equation 2 (Luque and Ferguson 2009), but reach an average maximum length of only 381.5 ± 3.5 cm (Fig. 21). In equation 1 and 2, x is the age of Beluga.

$$\text{Females: } 381.5e^{-7.56e^{-0.29x}} \qquad (2)$$

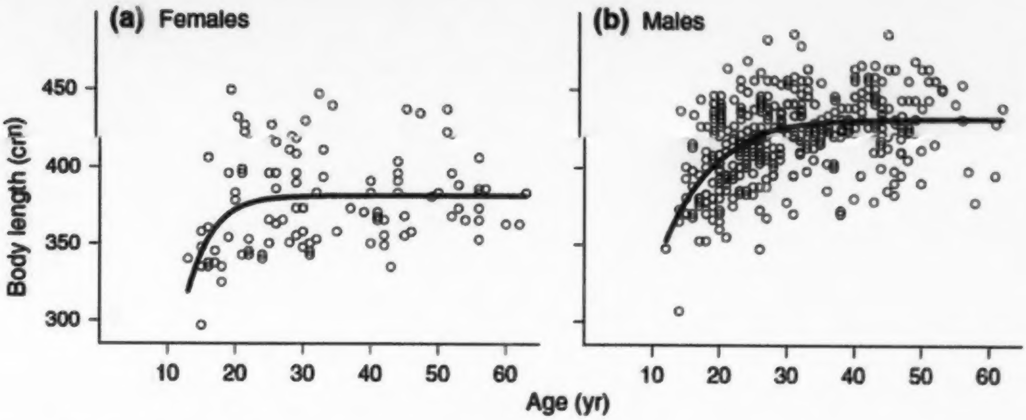


Figure 21. Relationship between body length and age (years) for female (a) and male (b) Beluga in the Beaufort Sea LOMA (from Luque and Ferguson 2009).

Diet and feeding

Tissue samples collected during community harvest are critical for monitoring contaminant loads and disease in the Beluga. Blubber samples collected during monitoring programs at Hendrickson Island and Browns Harbour near Paulatuk (2004-2005) were analyzed for fatty acids. This analysis provided information on the diet and feeding behaviour of the whales. Arctic Cod was identified as the main prey item for Beluga (Loseto et al. 2009). Beluga of all ages fed on Arctic Cod during spring and summer with larger animals feeding farther offshore than smaller animals, which fed on inshore prey assemblages including Arctic Cod (Loseto et al. 2009). Understanding patterns of resource use by Beluga is essential to assessing potential contaminant exposure and loading. Younger Beluga feeding close to shore may be exposed to lower contaminant levels since prey items in the estuarine-shelf area of the LOMA have lower mercury levels than offshore food webs in areas such as the Amundsen Gulf (Loseto et al. 2008). Therefore, samples collected during community monitoring allow not only for assessing current contaminant loads but can also be used to identify transfer pathways that may vary spatially and temporally within the LOMA.

Resilience to ecosystem change

There have been large-scale ecosystem changes (regime shifts) in the Bering and Beaufort Seas driven by changes in atmospheric circulation and sea surface temperatures. One strong regime shift occurred in 1977 and was linked to subsequent declines in fish-eating pinnipeds in western Alaska (e.g., Trites and Donnelly 2003). Regime shifts in either the Bering or Beaufort Sea may affect the growth and survival of the Eastern Beaufort Sea Beluga population as environmental changes would impact their winter and/or summer habitats, respectively.

Using the long-term dataset for Beluga in the LOMA, it was determined that Beluga born during regime shifts were not negatively affected with respect to body size or survival, relative to the overall Eastern Beaufort Sea population (Luque and Ferguson 2009). However, environmental regime shifts may have altered prey availability. Beluga growth

and survival appear to vary independently of regime shifts that negatively impacted other marine mammals in the Beaufort or Bering ecosystems. These results suggest that Beluga within the LOMA may be resilient to ecosystem changes. By adjusting their feeding behaviour with respect to what, where and when they eat, in their Bering Sea winter or Beaufort Sea summer habitat, Beluga may be able to mitigate negative effects of environmental change on their nutrition, growth and survival. Future monitoring will be required to determine how Beluga respond to cumulative effects of ecosystem change and potential increases in contaminant loads and/or disease.

7. FISHES OF THE YUKON NORTH SLOPE – UPDATING THE 1980S BASELINE

The majority of studies and surveys examining fisheries resources of the southern portion of the LOMA have been conducted in the nearshore waters in, and adjacent to, the Mackenzie River delta and the Tuktoyaktuk Peninsula. Conversely, relatively few studies have been conducted west of the Mackenzie River delta along the Yukon North Slope. Early studies of the Yukon coastal waters include: Craig and Mann (1974); Mann (1974); Griffiths et al. (1975); Kendel et al. (1975); and Baker (1985). As important as these early studies were, they were of relatively short durations within seasons and employed sampling gear which was selective of the fish species and sizes they captured. In 1986, a summer study of the fish community at Phillips Bay, Yukon (Bond and Erickson 1989) utilized shore-moored trapnets capturing virtually all sizes and species of fish moving through nearshore waters. Consequently, a remarkable 142 797 individual fish were sampled, covering a period from late June through mid-September. Twenty-one species of fish were documented for the area. Baseline information, for the most abundant of these, was established and included biological characteristics, population parameters, and seasonal movements.

The Yukon coast represents a narrow band of seasonally variable fish habitat that, during the 1986 study and at the current time, can be considered susceptible to natural and man-made forces, specifically hydrocarbon-related industrial development. The brackish waters of the Yukon coast during the open water season are a highly utilized habitat for both marine and anadromous fish. This habitat supports locally important species such as Dolly Varden Char and various whitefishes and ciscoes. The area also serves as a migration corridor between key habitats for transboundary species such as the Arctic Cisco. The restricted extent of Yukon coast habitat, coupled with its high utilization by fish, makes this an area that could easily be negatively impacted by natural or man-made forces.

The 1986 study by Bond and Erickson has remained the benchmark study for fish resources of nearshore Yukon coastal waters with no comprehensive fish study in the area for the following two decades. With renewed interest and activity in hydrocarbon exploration and production in the Beaufort Sea (both near- and offshore), there is an urgent need for reliable baseline data for the fish populations of the area to allow resource manager to monitor and mitigate the effects of development. For this reason, a comprehensive fish survey was again conducted in 2007 and 2008 at Phillips Bay to re-

examine the fish community along the Yukon coast. The objectives were first, to update the fisheries data baseline for the area and second, to assess changes in the area over the 20-year span between the two surveys. Identifying changes in fishes and their habitat prior to hydrocarbon development and attributing these changes to forces such as climate change will provide a more accurate context for future assessments of environmental change.

To make the comparison between the 1986 and 2007/2008 surveys as meaningful as possible, every effort was made to replicate the earlier study, including the location of the study (Phillips Bay), sampling gear and methods, time of year, duration of study and fish processing protocols. However, despite these efforts there were differences between the survey years including weather and water conditions, physical changes to the sampling sites (e.g., shore erosion, deposition of material in bays), specific configuration of sampling gear and the experience of survey crews. Also, it should be noted that the surveys represent just a few points in time over a 20-year period and that year-to-year variability of fish numbers and movements must also be taken into consideration. To obtain a rough estimate of inter-annual variability in fish numbers, the present study was conducted over two summer seasons. Unfortunately, the 1986 study was a single year effort. The variability between 2007 and 2008 appears to be less than the variability between 1986 and 2007/2008, suggesting that the changes observed over the 20-year interval may be meaningful.

Detailed analyses of the 2007/2008 surveys, including comparisons to the 1986 study, are presently ongoing. Tables 3 and 4 present the catch results, by species, for the 2007/2008 and the 1986 survey work for marine, anadromous and fresh water species, respectively. While the overall catch in 1986 was much larger (142 797 fish) than in either 2007 or 2008 (45 351 and 56 045, fish respectively) much of these seemingly large differences can be accounted for by the difference in sampling efforts between years. When catch-per-unit-effort (CPUE) data (i.e., the number of fish captured per given sampling effort) are examined, the catch results between 1986 and 2007/2008 are similar. For some species the CPUE increased while for others it decreased.

Species diversity along the coast was found to be very low in all survey years but increased slightly in the 2007/2008 survey. Twenty species of fish were captured by trapnet in 1986 with one additional species (Pacific Sand Lance, *Ammodytes hexapterus*) captured by beach seine. In the 2007/2008 survey, a total of 26 species were captured. The five species captured in 2007/2008 but not encountered in 1986 were: Starry Flounder (*Platichthys stellatus*), Arctic Lamprey (*Lethenteron camtschaticum*), Greenland Cod (*Gadus ogac*), Threespine Stickleback (*Gasterosteus aculeatus)*, Pond Smelt (*Hypomesus olidus)*, Chum Salmon (*Oncorhynchus keta*) and Pink Salmon (*Oncorhynchus gorbuscha*). Northern Pike (*Esox lucius*) was the only species of fish caught solely in 1986.

Table 3. Catch and percentage of total catch of Yukon coast marine species by species and year.

Marine Species	1986	2007	2008	Percent of total catch		
				1986	2007	2008
Arctic Flounder	44974	15314	16510	31.5	33.8	29.5
Fourhorn Sculpin	10530	2036	3462	7.4	4.5	6.2
Saffron Cod	2473	1904	5358	1.7	4.2	9.6
Starry Flounder	0	492	345	0	1.1	0.6
Pacific Herring	7	381	229	<0.1	0.8	0.4
Arctic Cod	154	24	78	<0.1	<0.1	0.1
Capelin (*Mallotus villosus*)	1	0	15	<0.1	0	<0.1
Blackline Prickleback (*Acantholumpenus mackayi*)	4	6	4	<0.1	<0.1	<0.1
Arctic Lamprey	0	1	1	0	0	0
Gelatinous Snailfish (*Liparis fabricii*)	10	0	1	<0.1	<0.1	<0.1
Greenland Cod	0	0	1	0	<0.1	<0.1
Threespine Stickleback	0	0	1	0	<0.1	<0.1
Totals	58152	20158	26005	40.7	44.5	46.4

Table 4. Catch and percentage of total catch of Yukon coast anadromous and fresh water species by species and year.

Anadromous and Fresh Water Species	1986	2007	2008	Percent of total catch		
				1986	2007	2008
Arctic Cisco	52988	9537	12755	37.1	21.0	22.8
Least Cisco	20482	6846	5729	14.3	15.1	10.2
Rainbow Smelt	7907	3976	8302	5.5	8.8	14.8
Lake Whitefish	417	2078	526	0.3	4.6	0.9
Broad Whitefish	937	1900	1555	0.7	4.2	2.8
Dolly Varden	1676	451	212	1.2	1.0	0.4
Inconnu	109	361	569	0.1	0.8	1.0
Pond Smelt	0	0	322	0	0	0.6
Pink Salmon	0	0	16	0	0	<0.1
Chum Salmon	0	0	5	0	0	<0.1
Total (anadromous species)	84516	25149	29991	59.2	55.5	53.5
Ninespine Stickleback	50	5	32	<0.1	<0.1	<0.1
Arctic Grayling	59	36	10	<0.1	<0.1	<0.1
Round Whitefish (*Prosopium cylindraceum*)	16	0	6	<0.1	<0.1	<0.1
Northern Pike	2	0	0	<0.1	<0.1	<0.1
Burbot (*Lota lota*)	1	3	1	<0.1	<0.1	<0.1
Total (fresh water species)	128	44	49	<0.1	<0.1	<0.1

Within the species list for the area, relatively few species comprise most of the catch. The same nine species account for 99.7, 97.2 and 97.2% of the total catch for years 1986, 2007 and 2008, respectively (Tables 3 and 4). The six most abundant species accounted for between 87.4 and 97.5% of the catch for all three years. The three most abundant

marine species in the three surveys were Arctic Flounder (*Pleuronectes glacialis*), Fourhorn Sculpin (*Myoxocephalus quadricornis)* and Saffron Cod, in that order, except that in 2008 there were more Saffron Cod captured than Fourhorn Sculpin (Table 3). The three most abundant anadromous species were Arctic Cisco, Least Cisco and Rainbow Smelt (*Osmerus mordax)*, in that order, for all three years (Table 4).

The composition of the total catch, in terms of the proportion of marine fish versus anadromous fish, was similar for all sampling years with marine fish comprising about 40 to 45% of the total catch and anadromous fish making up the remaining 55 to 60%. The proportional percentages for 1986, 2007 and 2008, respectively were 40.6, 42.5 and 45.3% marine versus 59.1, 54.7 and 51.9% anadromous suggesting that the number of anadromous fish may be increasing slightly relative to marine fish. Only a few fresh water species were encountered along the coastal waters and the numbers of fresh water fish captured are considered insignificant and incidental (<0.1%; Table 4). Of the fresh water species, it appears that Ninespine Stickleback (*Pungitius pungitius*) and Arctic Grayling (*Thymallus arcticus*) are the most likely to be encountered in these waters.

In addition to examining fish abundance, the present study also examines the condition of the fish in the area. Figure 22 shows the overall condition of a number of species as measured by Condition Factor K (equation 3), where W = weight in grams, L = length in mm, and N is a constant.

$$K = (10^N W)/L^3 \qquad (3)$$

K, therefore is a measure of the weight to length relationship of an individual fish and indicates the robustness or general condition of that fish. The mean K value for a large sample can indicate the overall health of the population. Using the mean K values from the 1986 survey as a baseline, most species appear to be in better condition in 2007/2008 than in 1986. Inconnu and Rainbow Smelt are little changed and only Broad Whitefish show a decrease in condition (Fig. 22).

It appears that the baseline fish populations of the nearshore Yukon coastal waters are very similar to that found in the area in 1986. The same small suite of species make up the majority of the total catch and are found in about the same relative abundance. Some changes in abundance are noted and five species not found in 1986 were captured in 2007/2008. Overall, the condition of fish within this important habitat of the LOMA appears to be good, relative to 1986.

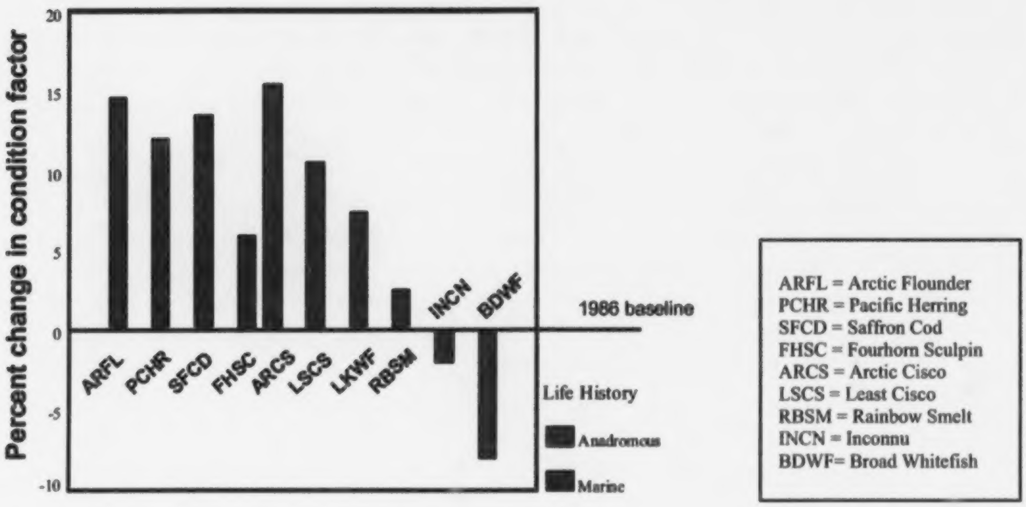


Figure 22. Percent change in condition factor of key Yukon coastal fish, 2007/2008 results compared to 1986 baseline.

8. SUMMER MARINE ECOSYSTEM STRUCTURE RELEVANT TO FISHES OF THE CANADIAN BEAUFORT SEA: THE CURRENT STATE OF KNOWLEDGE

During summer the southwest portion of the Beaufort Sea LOMA can be characterized by eight semi-distinct sub-ecosystems: 1) freshwater, 2) coastal, 3) nearshore benthic, 4) nearshore pelagic, 5) slope benthic, 6) slope pelagic, 7) deep basin, and 8) multi-year sea ice. Major defining characteristics, and relevance as fish habitat (where known), are presented in Figure 23. Fisheries research is not evenly distributed across the sub-ecosystems and there has been a bias towards anadromous versus marine species. Key gaps remain in describing marine fishes in the sub-ecosystems and their ecological roles are not yet fully understood.

In the 1970s and 1980s, fisheries research focused primarily on the coastal sub-ecosystem to address regulatory needs surrounding oil and gas exploration and development (e.g., Percy 1975; Stewart et al. 1993). This early work established the first comprehensive biological baselines for larval, anadromous and estuarine-adapted marine fishes of the coastal sub-ecosystem in summer (e.g., Chiperzak et al. 2003; Lawrence et al. 1984). The life-histories, biology and ecological roles of fishes in the nearshore, slope and basin sub-ecosystems are poorly understood. However, it is likely that marine fishes constitute a critical energetic link between upper (e.g., seals, Beluga) and lower (e.g., zooplankton, epibenthic invertebrates) trophic levels. Similarly, fish utilization of sea-ice remnants during summer are poorly studied, though, some pelagic species, such as Arctic Cod, likely use this habitat as a refuge from predators. Moreover, birds and seals which prey upon fishes and larger invertebrates concentrate at summer ice edges implying that relatively high abundances of pelagic fishes may occur in these areas.

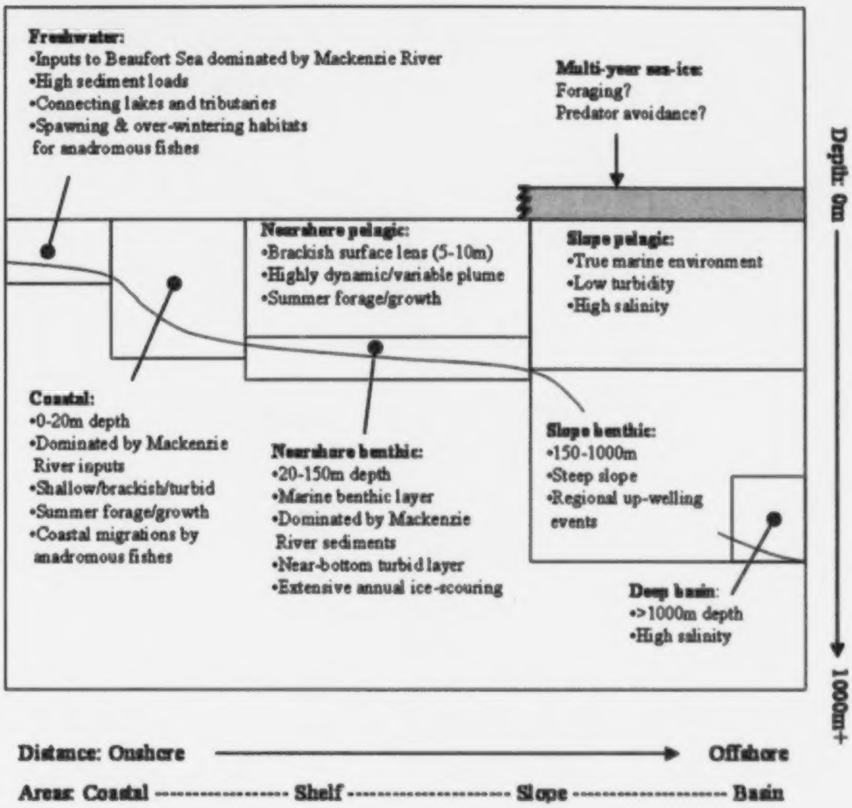


Figure 23. Schematic of the generalized sub-ecosystems relevant to fishes in the southwest portion of the Beaufort Sea LOMA in summer, extending offshore from the Mackenzie River. Similar structure is present throughout the area, however, the relative extent of a particular sub-ecosystem varies by location. General characteristics of the sub-ecosystems are provided.

Between 2003 and 2009, the Northern Coastal Marine Studies (NCMS) program, funded through Indian and Northern Affairs Canada's Hydrocarbon Initiative, studied the physical and biological nature of the nearshore sub-ecosystem. The biological components of NCMS sought to address knowledge gaps regarding species composition, distribution and trophic interactions of biota (i.e., fishes, benthic invertebrates, ichthyoplankton and zooplankton) as they relate to environmental drivers. During the 2006 to 2009 sampling seasons, small-bodied demersal marine fishes were sampled using a benthic beam trawl at a combination of transect-based stations and naturally occurring physical features (e.g., ice scours, gas vents) or areas that are considered to be significant from a biological and/or oceanographic perspective (e.g., whale feeding areas, upwelling locations) (Majewski et al. 2009b, 2011, Fig. 24). In 2004 and 2005, opportunistic gill-netting and limited mid-water trawling were conducted in nearshore waters, generally within the 50 m isobath (Majewski et al. 2006, 2009a). Though limited by gear type and fishing effort, the results of the NCMS fishing program expanded the information base on:

- Beaufort Sea marine fish distributions in the context of key oceanographic and habitat parameters.
- Our understanding of fish community species composition.
- The basic biology and genetics of the fishes and trophic structure, by providing data and tissues for follow-on analyses.
- Energy pathways within the nearshore sub-ecosystems.

During the four years of benthic trawling, a total of 40 species were identified from the outer coastal and nearshore benthic sub-ecosystems. Catch data and basic biological data from fish captured during the NCMS program are summarized in Majewski et al. (2006, 2009a, 2009b, 2011) and Lowdon et al. (2011).

Follow-on investigations into the community composition and habitat associations of marine fishes are ongoing (Lynn 2010; Majewski et al. in prep). Preliminary analyses indicate marine fish community structuring within the nearshore and outer coastal sub-ecosystems. Figure 25 is an ordination plot resulting from non-metric multi-dimensional scaling (MDS) of species abundances across stations sampled on the Mackenzie Shelf between 2006 and 2009.

Figure 24. Transects and feature-based trawling stations for marine fishes sampled during the Northern Coastal Marine Studies program, 2006-2009.

The MDS indicates a shift in fish species composition at approximately 50 m depth, suggesting the presence of shallow (<50 m) and deepwater (>50 m) assemblages on the shelf. Stations prefixed with A and C in Figure 25 are representative of repeat sampling at one transect in 2006 and 2009. The MDS ordination indicates interannual variability in species composition and abundance at this particular transect, thus the stability of these associations is uncertain. Despite the moderate two-dimensional stress value (0.18) of the

MDS ordination, this finding was also reflected in a hierarchical cluster analysis (PRIMER-E Ltd) of the same data, as well as in the following analyses.

A non-parametric, permutation based, Analysis of Similarity (ANOSIM, PRIMER-E Ltd.) was used to test the null hypotheses that, based on the similarity matrix of relative abundances, there are no differences in assemblages between: 1) stations <50 m and stations >50 m depth, and 2) stations sampled in 2006 and 2009 at the same location (prefixed A and C, respectively, in Fig. 25). The ANOSIM test rejected both null hypotheses at $p<0.001$ ($R = 0.509$) and $p<0.01$ ($R = 0.448$). The ANOSIM test statistic R is based on the corresponding rank similarities between the samples in the underlying similarity matrix. R will typically fall between 0 and 1, with $R \approx 0$ indicating that the null hypothesis is true (i.e., similarities between and within sites are the same on average) and $R = 1$ indicating that all replicates within sites are more similar to each other than any replicates from different sites (Clarke and Warwick 2001). Within the ANOSIM test, the reliability of the p-value is highly dependent on the number of possible permutations in the test. Considering the number of permutations in both null hypotheses tested here, 999 and 715, respectively, the combination of low p-values with moderate R statistics indicate that we can reliably reject both null hypotheses.

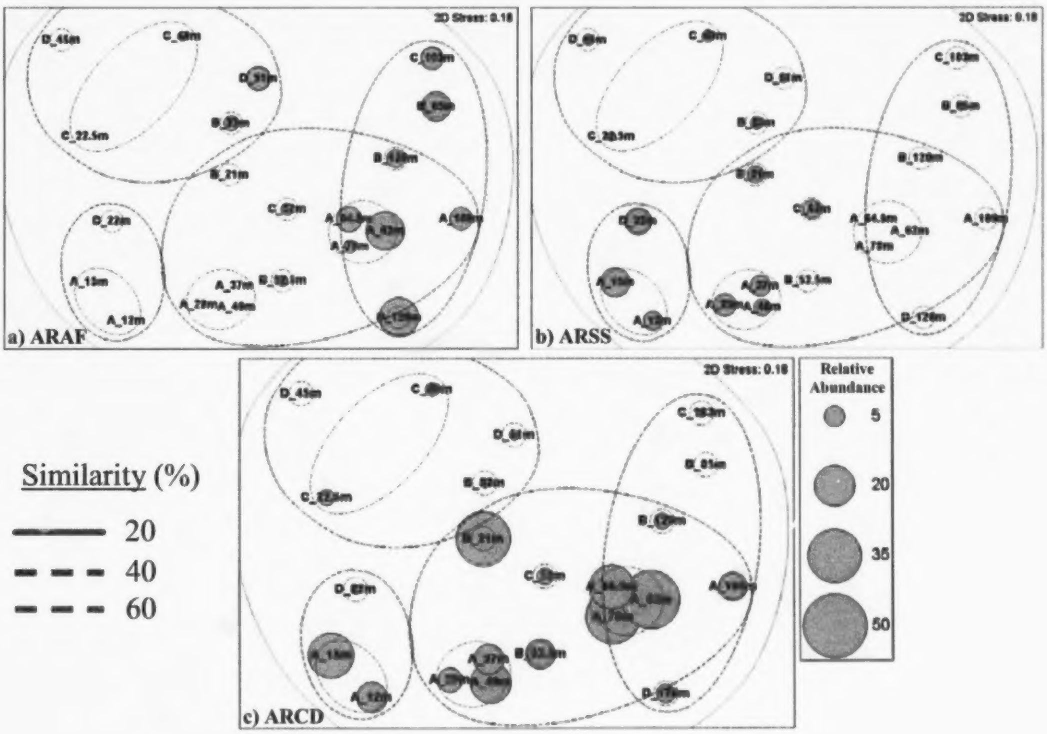


Figure 25. Non-metric multidimensional scaling ordination plot of station groupings on the Mackenzie Shelf based on species composition and abundances. Bubble plots for relative abundances of a) Arctic Alligatorfish (ARAF), b) Arctic Staghorn Sculpin (ARSS), and c) Arctic Cod (ARCD) have been overlaid for comparison across stations. Groupings from a hierarchical cluster analysis of the same data are superimposed at similarity levels of 20, 40 and 60%.

A SIMPER test (PRIMER-E Ltd.) was applied to determine discriminating species amongst stations less than and deeper than 50 m. The SIMPER test computes the average dissimilarity between all pairs of intergroup samples, and then dissociates the average into a separate contribution from each species (Clarke and Warwick 2001). Arctic Alligatorfish (*Ulcina olrikii*) accounted for the highest proportion of the average dissimilarity between groups at 12.52%. In combination with Arctic Alligatorfish, Stout Eelblenny (*Anisarchus medius*) (11.05%), Arctic Cod (10.60%), Arctic Staghorn Sculpin (*Gymnocanthus tricuspis*) (9.09%) and Spatulate Sculpin (*Icelus spatula*) (7.60%) accounted for approximately 50% of the average dissimilarity between the <50 m and >50 m assemblages.

The SIMPER test also yields the contribution of each species to the average similarity within each of the groups, identifying species that typify a group. For the <50 m group, Arctic Staghorn Sculpin accounted for 24.52% of the average similarity between all pairs of sites. The other main contributors were Arctic Cod at 22.88% and Canadian Eelpout (*Lycodes polaris*) at 19.36%. For the >50 m group, Arctic Alligatorfish accounted for 28.03% of the average similarity within stations. Arctic Cod also typified the >50 m group (21.30%) reflecting the ubiquitous presence of this species in benthic trawl catches of the study (Fig. 25c). Spatulate Sculpin contributed prominently to the average similarity within stations of the >50 m group at 17.20%. Figure 25 illustrates the differences in distributions and relative abundances of three species that contribute prominently to the average dissimilarity between the <50 m and >50 m groups, and also typify their respective groups.

Based on the NCMS fishing program and earlier studies, the current knowledge of fishes in the Beaufort Sea sub-ecosystems during summer can be summarized as follows. The coastal sub-ecosystem is dominated by turbid Mackenzie River inputs, creating a brackish environment that provides summer foraging habitat and coastal migratory pathways for anadromous fishes including whitefishes (e.g., Broad Whitefish, Arctic Cisco and Least Cisco) and Dolly Varden. Estuarine-adapted marine fishes also inhabit the coastal sub-ecosystem in summer, presumably to forage. Prominent marine benthic fishes that can be found in coastal waters include: sculpins (e.g., Fourhorn Sculpin and Arctic Staghorn Sculpin); flatfishes (e.g., Starry Flounder (*Platichthys stellatus*) and Arctic Flounder); and Stout Eelblenny. Common marine pelagic fishes, often captured during subsistence fishing in coastal waters, include Pacific Herring, Saffron Cod and Rainbow Smelt. The nearshore pelagic sub-ecosystem is characterized by a transition from the Mackenzie-dominated inner-shelf region to a true marine environment in the outer-shelf region. Fish assemblages in this transition zone, generally between the 30-50 m isobaths, overlap with those of the coastal sub-ecosystem. Species within the marine pelagic waters of the outer-shelf have not been comprehensively sampled. However, work in adjacent Alaskan waters indicated that Arctic Cod account for much of the fish biomass in the marine pelagic zone of the Beaufort Sea (Logerwell et al. 2010). Limited survey work suggests that most of the fish diversity in the nearshore sub-ecosystems occurs in the benthic zone (Majewski et al. 2006, 2009a, 2009b, 2011; Rand and Logerwell 2011). Most of these benthic species are small-bodied, epibenthic feeders. Common demersal fishes inhabiting the Mackenzie Shelf include: Arctic Alligatorfish;

eelpouts (e.g., Arctic Eelpout (*Lycodes reticulatus*) and Canadian Eelpout)); sculpins (e.g., Ribbed Sculpin (*Triglops pingelii*) and Twohorn Sculpin (*Icelus bicornis*)); Kelp Snailfish (*Liparis tunicatus*) and Gelatinous Seasnail (*Liparis fabricii*); and pricklebacks (e.g., Stout Eelblenny and Slender Eelblenny (*Lumpenus fabricii*)). In recent benthic trawl surveys, Arctic Cod have dominated catches at both the shelf and slope stations (Majewski et al. 2009b, 2011; Rand and Logerwell 2011). Deeper slope pelagic and benthic areas have not been effectively sampled in the Canadian portion of the Beaufort Sea, however, previous work near Sachs Harbour, Banks Island, captured Greenland Halibut (*Reinhardtius hippoglossoides*) on baited long-lines at approximately 430 m depth (Chiperzak et al. 1995).

Hydrocarbon exploration in the Beaufort Sea has moved further offshore in the last decade with exploration licenses recently issued in off-shelf waters up to 1200 m depth. Thus, future hydrocarbon development scenarios in the Beaufort Sea LOMA could encompass the coastal, nearshore, and slope sub-ecosystems. In addition to hydrocarbon activities, human-driven climate change, climate variability, and new colonizers and invasive species could impose rapid environmental change and cumulative impacts on Beaufort Sea marine fishes and their habitats, both directly and indirectly. A comprehensive baseline understanding of the distributions, diversity, relative abundances and key habitat associations for marine fishes is required to effectively gauge impacts and to support associated regulatory decisions. The sub-ecosystems delineated in the Beaufort Sea are connected through physical and chemical processes such as material and nutrient transfers. They are also connected by biotic associations that include fish migratory pathways among the sub-ecosystems and differential habitat use by particular life stages within species. In order to address complex regulatory demands, an understanding of these ecological connections between the sub-ecosystems is essential. This includes an understanding of the habitat requirements of fishes and other biota across life-history stages as well as knowledge of associated trophic linkages and energy pathways within and amongst sub-ecosystems.

9. MARINE PROTECTED AREAS - CURRENT AND FUTURE

The TNMPA in the Beaufort Sea LOMA was officially announced on August 26, 2010. This is Canada's first Arctic MPA and it contains three areas: Niaqunnaq, Okeevik, and Kittigaryuit (Fig. 26), all of which have been traditionally used by the Inuvialuit and are important from a cultural, subsistence and economic perspective. TNMPA covers approximately 1800 km^2, including portions of the Mackenzie River delta and estuary. The primary conservation objective of the TNMPA is to conserve and protect Beluga and other marine species (anadromous fishes, waterfowl and seabirds), their habitats and their supporting ecosystem. This conservation objective strengthens and compliments the Beaufort Sea Beluga Management Plan (BSBMP) that works to ensure the long-term sustainable management of the Eastern Beaufort Sea population of Beluga, and their habitat (Loseto et al. 2010).

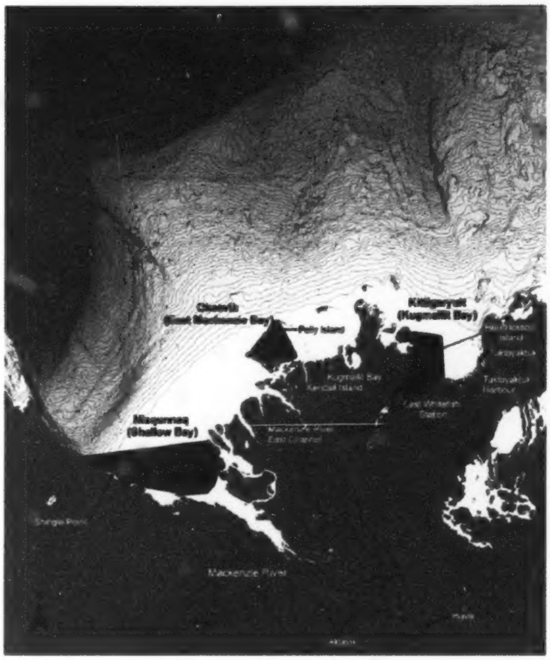


Figure 26. The three TNMPA areas within the Mackenzie River delta/estuary portion of the Beaufort Sea LOMA. Depth contours are at 5m intervals. (From Loseto et al. 2010).

In 2010, DFO together with Aklavik community members, conducted an ecosystem assessment within the Shallow Bay (Niaqunnaq) area of the TNMPA as part of the Arctic Coastal Ecosystem Studies (ACES) program. As the first ecosystem assessment of the area, the work will contribute to determining indicators for monitoring the effects of industry and climate change within the TNMPA. During ACES, moorings were deployed to measure oceanographic characteristics and acoustic sensors were deployed that detected Beluga within the area (E. Chmelnitsky and L. Loseto, pers. comm.). Fish surveys were conducted to provide diversity and population information for the area. In addition, water chemistry, contaminants (i.e., mercury) and the abundance and biomass of microorganisms, phytoplankton and zooplankton were studied. Preliminary results (Fig. 27) show across-bay variation with the input of sediments from the Mackenzie River that impact primary productivity within the system. The entrance of nutrient-poor marine waters on the western side of the bay is also evident (Fig. 27c, d).

An Area of Interest (AOI) in Darnley Bay near Paulatuk (Fig. 1) is currently undergoing assessment for MPA designation (DFO 2011). Conservation objectives are being developed based on offshore biological production associated with the polynya and sea-ice edge as well as critical nearshore Arctic Char habitat within the Darnley Bay/Amundsen Gulf region. An Ecosystem Overview Report for the Darnley Bay AOI is currently in press (Table 1) moving the process towards a second MPA within the Beaufort Sea LOMA.

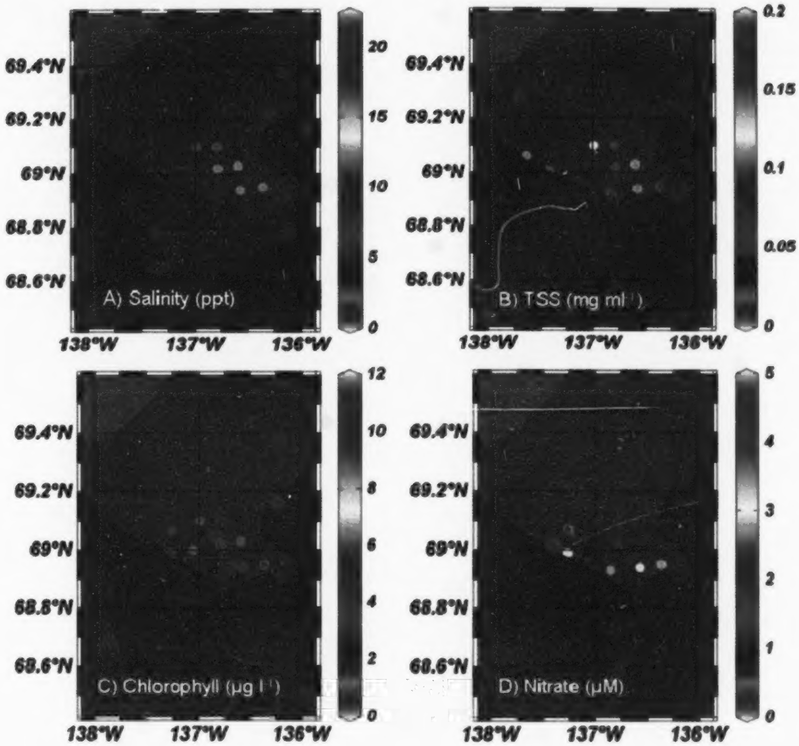


Figure 27. Salinity values and total suspended sediments (TSS), chlorophyll and nitrate concentrations in Shallow Bay, ACES study 2010.

ACKNOWLEDGEMENTS

This report represents many years of work by multiple research teams. We acknowledge all the officers and crews of the various vessels involved as well as all communities that have supported this work. We thank S. Ferguson, L. Harwood, S. Luque, N. Morata and W. Walkusz for reviewing select sections of the report as well as L. Brown and J. Paulic for their review of the entire document.

REFERENCES

Baker, R.F. 1985. A fisheries survey of Herschel Island, Yukon Territory from 9 July to 12 August, 1985. Prepared for department of Renewable Resources, Yukon Territory by North/South Consultants Inc., Winnipeg, MB. 44 p.

Bond, W.A., Erickson, R.N. 1989. Summer studies of the nearshore fish community at Phillips Bay, Beaufort Sea coast, Yukon. Can. Tech. Rep. Fish. Aquat. Sci. 1676: vi + 102 p.

Chiperzak, D.B., Saurette, F., Raddi, P. 1995. First record of Greenland Halibut (*Reinhardtius hippoglossoides*) in the Beaufort Sea (Arctic Ocean). Arctic. 48: 368–371.

Chiperzak, D.B., Hopky, G.E., Lawrence, M.J., Schmid, D.F., Reist, J.D. 2003. Larval and post-larval fish data from the Canadian Beaufort Sea shelf, July to September, 1987. Can. Data Rep. Fish. Aquat. Sci. 1121: iv + 84 p.

Clarke, K.R., Warwick, R.M. 2001. Change in marine communities: an approach to statistical analysis and interpretation, 2nd edition. PRIMER-E: Plymouth.

Comeau, S., Gorsky, G., Jeffree, R., Teyssié, J.-L., Gattuso, J.-P. 2009. Impact of ocean acidification on a key Arctic pelagic mollusk (*Limacina helicina*), Biogeosciences. 6: 1877–1882.

Cobb, D., Fast, H., Papst, M.H., Rosenberg, D., Rutherford, R., Sareault, J.E. 2008. Beaufort Sea Large Ocean Management Area: Ecosystem overview and assessment report. Can. Tech. Rep. Fish. Aquat. Sci. 2780: ii-ix + 188 p.

COSEWIC. 2004. COSEWIC assessment and update status report on the Beluga Whale *Delphinapterus leucas* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. ix + 70 p.

Craig, P., Mann, G.J. 1974. Life history and distribution of the Arctic cisco (*Coregonus autumnalis*) along the Beaufort Sea coastline in Alaska and the Yukon Territory. *In* McCart, P. (ed.). Life histories of anadromous and freshwater fishes in the Western Arctic. Arctic Gas Biol. Rep. Ser. 20: 33 p.

Darnis, G., Barber, D.G., Fortier, L. 2008. Sea ice and the onshore–offshore gradient in pre-winter zooplankton assemblages in southeastern Beaufort Sea. J. Mar. Syst. 74: 994–1011.

DFO. 2010. Review of Alternate Ballast Water Exchange Zones for vessel traffic to Newfoundland and Labrador and the Canadian Arctic. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/026.

DFO. 2011. Identification of conservation objectives and boundary delineation for the Darnley Bay Area of Interest (AOI). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/009.

Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A. 2009. Ocean acidification: the other CO_2 problem. Annu. Rev. Mar. Sci. 1: 169–192.

Feely, R.A., Sabine, C.L., Hernandez-Ayon, J.M., Ianson, D., Hales, B. 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. Science. 320: 1490–1492.

George, J.C., Clark, C., Carroll, G.M., Ellison, W.T. 1989. Observations on the ice-breaking and ice navigation behavior of migrating bowhead whales (*Balaena mysticetus*) near Point Barrow Alaska spring 1985. Arctic 42: 24–30.

Grainger, E.H. 1975. Biological productivity of the southern Beaufort Sea: The physical–chemical environment and the plankton. Beaufort Sea Technical Report, Victoria, BC.

Grainger, E.H., Grohe, K. 1975. Zooplankton data from the Beaufort Sea, 1951 to 1975. Environment Canada, Fisheries and Marine Service, Technical Report No. 591. Arctic Biological Station. St. Anne de Bellevue, Québec.

Griffiths, W., Craig, P., Wlader, G., Mann, G. 1975. Fisheries investigations in a coastal region of the Beaufort Sea (Nunaluk Lagoon, Yukon Territoy). *In* Craig, P. (ed.). Fisheries investigations in a coastal region of the Beaufort Sea. Arctic Gas Biol. Rep. Ser. 34: 219 p.

Hartwig, L. 2009. Mapping traditional knowledge related to the identification of Ecologically and Biologically Significant Areas in the Beaufort Sea. Can. Manuscript Rep. Fish. Aquat. Sci. 2895: iii + 25 p.

Harwood, L.A., Norton, P., Day, B., Hall, P.A. 2002. The harvest of beluga whales in Canada's western Arctic: Hunter-based monitoring of the size and composition of the Catch. Arctic 55: 10–20.

Harwood, L.A., Auld, J., Joynt, A., Moore, S.E. 2010. Distribution of bowhead whales in the SE Beaufort Sea during late summer, 2007-2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/111. iv + 22 p.

Jutterström, S., Anderson, L.G. 2005. The saturation of calcite and aragonite in the Arctic Ocean. Mar. Chem. 94: 101–110.

Kendel, R.E., Johnston, R.A.C., Lobsiger, U., Kozak, M.D. 1975. Fishes of the Yukon coast. Beaufort Sea Project, Tech. Rep. No. 6, Beaufort Sea Project Office, Victoria, B.C. 114 p.

Koski, W.R., Zeh, J.E., Mocklin, J., Davis, A.R., Rugh, D.J., George, J.C., Suydam, R. 2010. Abundance of Bering-Chukchi-Beaufort bowhead whales (*Balaena mysticetus*) in 2004 estimated from photo-identification data. J. Cetacean Res. Manage.11: 89–99.

Lawrence, M.J., Lacho, G., Davies, S. 1984. A survey of the coastal fishes of the southeastern Beaufort Sea. Can. Tech. Rep. Fish. Aquat. Sci. 1220: x + 178 p.

Li, W.K., McLaughlin, F.A., Lovejoy, C., Carmack, E.C. 2009. Smallest algae thrive as the Arctic Ocean freshens. Science. 326: 539, doi:10.1126/science.1179798.

Lischka, S., Buedenbender, J., Boxhammer, T., Riebesell, U. 2011. Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod *Limacina helicina*: mortality, shell degradation, and shell growth. Biogeosciences. 8: 919–932.

Logerwell, E, Rand, K., Parker-Stetter, S., Horne, J., Weingartner, T., Bluhm, B. 2010. Beaufort Sea marine fish monitoring 2008: Pilot survey and test of hypotheses. Final Report. Prepared for Minerals Management Service, U.S. Department of the Interior. BOEMRE 2010-048, 263 p.

Loseto, L.L., Stern, G.A., Deibel, D., Connelly, T.L., Prokopowicz, A., Lean, D.S.R., Fortier, L., Ferguson, S.H. 2008. Linking mercury exposure to habitat and feeding behaviour in Beaufort Sea Beluga whales. J. Mar. Sys. 74: 1012–1024.

Loseto, L.L., Stern, G.A., Connelly, T.L., Deibel, D., Gemmill, B., Prokopowicz, A., Fortier, L., Ferguson, S.H. 2009. Summer diet of beluga whales inferred by fatty acid analysis of the eastern Beaufort Sea food web. J. Exp. Mar. Biol. Ecol. 374: 12–18.

Loseto, L., Wazny, T., Cleator, H., Ayles, B., Cobb, D., Harwood, L., Michel, C., Nielsen, O., Paulic, J., Postma, L., Ramlal, P., Reist, J., Richard, P., Ross, P.S., Solomon, S., Walkusz, W., Weilgart, L., Williams, B. 2010. Information in support of indicator selection for monitoring the Tarium Niryutait Marine Protected Area (TNMPA). DFO Can. Sci. Advis. Sec. Res, Doc. 2010/094. vi + 47 p.

Lowdon, M.K., Majewski, A.R., Reist., J.D. 2011. Fish catch data from Herschel Island, Yukon Territory, and other offshore sites in the Canadian Beaufort Sea, July and August 2008, aboard the CCGS Nahidik. Can. Data Rep. Fish. Aquat. Sci. 1237: vi + 99 p.

Luque, S.P., Ferguson, S.H. 2006. Age structure, growth, and mortality of eastern Beaufort Sea beluga (*Delphinapterus leucas*): a comparison among Canadian populations. Canada/Inuvialuit Fisheries Joint Management Committee Technical Report Series. 27 p.

Luque, S.P., Ferguson, S.H. 2009. Ecosystem regime shifts have not affected growth and survivorship of eastern Beaufort Sea belugas. Oecologia. 160: 367–378.

Luque, S.P., Ferguson, S.H. 2010. Age structure, growth, mortality, and density of belugas (*Delphinapterus leucas*) in the Canadian Arctic: responses to environment? Polar Biol. 33: 163–178.

Lynn, B.R. 2010. Location, location, location: the influence of environmental variables on fish species composition in the Canadian Beaufort Sea. Honours Thesis, University of Winnipeg, Winnipeg, MB. 62 p.

Macdonald R.W., Harner, T., Fyfe, J. 2005. Recent climate change in the Canadian Arctic and its impact on contaminant pathways. Sci. Total Environ. 342: 5–86.

Majewski, A.R., Reist, J.D., Sareault, J.E. 2006. Fish catch data from offshore sites in the Mackenzie River estuary and Beaufort Sea during the open water season, August 2004, aboard the CCGS Nahidik. Can. Manuscr. Rep. Fish. Aquat. Sci. 2771: vi + 37 p.

Majewski, A.R., Reist, J.D., Park, B.J., Sareault, J.E., Lowdon, M.K. 2009a. Fish catch data from offshore sites in the Mackenzie River estuary and Beaufort Sea during the open water season, July and August, 2005, aboard the CCGS Nahidik. Can. Data Rep. Fish. Aquat. Sci. 1204: vii + 53 p.

Majewski, A.R., Reist, J.D., Park, B.J., Lowdon, M.K. 2009b. Fish catch data from offshore sites in the Mackenzie River estuary and Beaufort Sea during the open water season, July and August, 2006, aboard the CCGS Nahidik. Can. Data Rep. Fish. Aquat. Sci. 1218: vi + 37 p.

Majewski, A.R., Lowdon, M.K., Reist, J.D., Park, B.J. 2011. Fish catch data from Herschel Island, Yukon Territory, and other offshore sites in the Canadian Beaufort Sea, July and August 2007, aboard the CCGS Nahidik. Can. Data Rep. Fish. Aquat. Sci. 1231: vi + 50 p.

Majewski, A.R, Lynn, B.R., Williams, W., MacKillop, K., Conlan, K., Walkusz, W., Reist, J.D. *In prep*. Spatial distributions and habitat associations of marine fishes in the Canadian Beaufort Sea. Polar Biol.

Mann, G.J. 1974. Life history types of the Least Cisco (*Coregonus sardinella*, Valenciennes) in the Yukon Territory north slope and eastern Mackenzie River delta drainages. *In* McCart, P. (ed.). Life histories of three species of freshwater fishes in Beaufort Sea drainages, Yukon Territory. Arctic Gas Biol. Rep. Ser. 18: 132 p.

Mason, G.K., Solomon, S.M. 2007. Past and future forcing of Beaufort Sea coastal change. Atmos.-Ocean. 45: 107–122.

McLaughlin, F.A., Carmack E.C. 2010. Deepening of the nutricline and chlorophyll maximum in the Canada Basin interior, 2003–2009. Geophys. Res. Lett. 37: L24602, doi:10.1029/2010GL045459.

Melling, H., Riedel, D.A., Gedalof, Z. 2005. Trends in the draft and extent of seasonal pack ice, Canadian Beaufort Sea. Geophys. Res. Lett. 32: L24501.

Millero, F.J. 1996. Chemical oceanography. CRC Press, Boca Raton. 1–469 p.

Percy, R. 1975. Fishes of the outer Mackenzie Delta. Beaufort Sea Project Technical Report. 8: vi + 114 p.

Proshutinsky, A., Krishfield, R., Timmermans, M.-L., Toole, J., Carmack, E., McLaughlin, F., Zimmerman, S., Itoh, M., Shimada, K. 2009. The Beaufort Gyre freshwater reservoir: state and variability from observations. J. Geophys. Res. 114: C00A10, doi:10.1029/2008JC005104.

Prouse, T.D., Furgal, C., Melling, H., Smith, S.L. 2009. Implications of climate change for northern Canada: The physical environment. AMBIO. 38: 266–271.

Quakenbush, L.T., Citta, J.J., George, J.C., Small, R.J., Heidi-Jorgensen, M.P. 2010. Fall and winter movements of bowhead whales (*Balaena mysticetus*) in the Chukchi Sea and within a potential petroleum development area. Arctic 63: 289–307.

Rand, K.M., Logerwell, E.A. 2011. The first demersal trawl survey of benthic fish and invertebrates in the Beaufort Sea since the late 1970s. Polar Biol. 34: 475–488.

Steinacher, M., Joos, F., Frölicher, T.L., Plattner, G.-K., Doney, S.C. 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. Biogeosciences. 6: 515–533.

Stephenson, S.A., Hartwig, L. 2009. The Yukon North Slope pilot project: An environmental risk characterization using a pathways of effects model. Can. Manuscr. Rep. Fish. Aquat. Sci. 2896: vi + 57 p.

Stewart, D.B., Ratynski, R.A., Bernier, L.M.J., Ramsey, D.J. 1993. A fishery development strategy for the Canadian Beaufort Sea-Amundsen Gulf area. Can. Tech. Rep. Fish. Aquat. Sci. 191 0: v + 127 p.

Trites A.W., Donnelly, C.P. 2003. The decline of Steller sea lions *Eumetopias jubatus* in Alaska: a review of the nutritional stress hypothesis. Mammal Rev. 33: 3–28.

Walkusz, W. Williams, W., Harwood, L., Moore, S., Stewart, B., Kwasniewski, S. *Submitted.* Composition, biomass and energetic content of biota in the vicinity of feeding bowhead whales (*Balaena mysticetus*) in the Cape Bathurst upwelling region (south eastern Beaufort Sea). Deep Sea Res. I.

Walkusz, W., Paulic, J.E., Kwaśniewski, S., Williams, W.J., Wong, S., Papst, M.H. 2010. Distribution, diversity and biomass of summer zooplankton from the coastal Canadian Beaufort Sea. Polar Biol. 33: 321–335.

Williams, W.J., Melling, H., Carmack, E.C., Ingram, G. 2008. Kugmallit Valley as a conduit for cross-shelf exchange on the Mackenzie Shelf in the Beaufort Sea. J. Geophys. Res. 113: C02007, doi:10.1029/2006JC003591.

Yamamoto-Kawai, M., McLaughlin, F.A., Carmack, E.C., Nishino, S., Shimada, K. 2009. Aragonite undersaturation in the Arctic Ocean: Effects of ocean acidification and sea ice melt. Science. 326: 1098–1100.

Yamamoto-Kawai, M., McLaughlin, F.A., Carmack, E.C. 2011. Effects of ocean acidification, warming and melting of sea ice on aragonite saturation of the Canada Basin surface water. Geophys. Res. Lett. 38: L03601, doi:10.1029/2010GL045501.

Zeh, J.E., Punt, A.E. 2005. Updated 1978-2001 abundance estimates and their correlations for the Bering-Chukchi-Beaufort Seas stock of bowhead whales. J. Cetacean Res. Manage. 7: 169–175.

PERSONAL COMMUNICATIONS

Elly Chmelnitsky, Fisheries and Oceans Canada, Winnipeg, MB
Lisa Loseto, Fisheries and Oceans Canada, Winnipeg, MB
Humfrey Melling, Fisheries and Oceans Canada, Sydney, BC
William Williams, Fisheries and Oceans Canada, Sydney, BC
Michiyo Yamamoto-Kawai, Fisheries and Oceans Canada, Sydney, BC